FINAL REPORT

Ultraviolet (UV)-Curable Coatings for Aerospace Applications

ESTCP Project WP-0804

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One area where the Department of Defense (DoD) continues to spend millions of dollars each year is painting operations, specifically the use of solvent-borne organic coatings to protect weapon system substrates. Continued use of these coatings results in the emissions of high volumes of volatile organic compounds (VOCs) and hazardous air pollutants (HAPs). In addition, their use also presents a significant production burden associated with cure times before handling, masking, recoating, or flying. Ultraviolet- (UV-) curable coatings are an alternative to conventional isocyanate-cure polyurethane and epoxy coatings. UV-curable coatings can be manufactured to be HAP and isocyanate-free using only exempt solvents. They are single- component, high-solid (nearly 50%), cross-linked coatings that are cured in minutes by brief exposure to intense UV light

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ACRONYMS

ACGIH	American Council of Government Industrial Hygienists
AFB	Air Force Base
AFRL	Air Force Research Laboratory
APC	Advanced Performance Coating
ASTM	American Society for Testing and Materials
BMS	Bayer Material Science
CAA	Clean Air Act
COTS	Commercial-off-the-shelf
CTC	Concurrent Technologies Corporation
CTIO	Coatings Technology Integration Office
CWA	Clean Water Act
Dem/Val	Demonstrate/validate
DFT	Dry film thickness
DNT	Did not test
DoD	Department of Defense
DSM	DSM Desotech
ECAM	Environmental Cost Analysis Methodology
ELT	Extended Life Topcoat
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
HAP	Hazardous air pollutant
Hazmat	Hazardous material
HVLP	High volume low pressure
ICBA	Initial Cost Benefit Analysis
JTP	Joint Test Protocol
MEK	Methyl ethyl ketone
Mil-spec	Military specification
Min	Minimum
MSDS	Materials Data Safety Sheet
mJ/cm^2	Milijoules per centimeter squared
mW/cm2	Miliwatts per centimeter squared
NEC	National Electrical Code
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institute of Standards and Technology
nm	Nanometers
OO-ALC	Ogden Air Logistics Complex
Opt	Optimum
P2	Pollution prevention
PI	Principal Investigator
PSI	Pounds per square inch
QPL	Qualified Products List
RCRA	Resource Conservation and Recovery Act

RH	Relative humidity
SBIR	Small Business Innovation Research
SPO	System Program Office
TO	Technical Order
USA	United States of America
USD	United States Dollars
USN	United States Navy
USAF	United States Air Force
USCG	United States Coast Guard
UV	Ultraviolet
UV-PUD	UV-curable polyurethane dispersions
VOC	Volatile organic compound
W	Watt
WFT	Wet film thickness

EXECUTIVE SUMMARY

One area where the Department of Defense (DoD) continues to spend millions of dollars each year is painting operations, specifically the use of solvent-borne organic coatings to protect weapon system substrates. Continued use of these coatings results in the emissions of high volumes of volatile organic compounds (VOCs) and hazardous air pollutants (HAPs). In addition, their use also presents a significant production burden associated with cure times before handling, masking, recoating, or flying. Ultraviolet- (UV-) curable coatings are an alternative to conventional isocyanate-cure polyurethane and epoxy coatings. UV-curable coatings can be manufactured to be HAP and isocyanate-free using only exempt solvents. They are single-component, high-solid (nearly 50%), cross-linked coatings that are cured in minutes by brief exposure to intense UV light. Benefits of successful implementation of UV-curable coatings include:

- Reduced VOC and HAP emissions
- Reduced hazardous waste
- Reduced waste management costs
- Reduced regulatory financial liabilities
- Enhanced environmental leadership role
- Applied using current painting capital equipment [applied through current spray technology, high volume low pressure (HVLP) and traditional coating techniques (i.e., brush, roll or spray)]
- Decreased process flow time and increased weapon system availability.

Many industrial applications are designed for "full spectrum" UV cure, in which the photoinitiators are designed for cure with highly intense (more than 500 mW/cm^2) UV light with multiple spectral absorption peaks across the UVA, UVB, and UVC spectrums. However, these full spectrum cures are hazardous to personnel, requiring enclosed cure areas and full protective gear for anyone entering those areas. For this reason, all UV-curable coatings utilized in this project were formulated for near-visible light UVA cure and low intensities.

This project tested and evaluated UV-curable coatings designed to serve as drop-in replacements for current DoD aerospace topcoats. The commercially available, UV-curable coatings coming closest to meeting performance requirements were topcoats. Topcoats are applied to a higher thickness than primer coatings, providing greater potential for environmental benefit. Since topcoats require significantly longer cure times, the UV-cure topcoats also allow for greater process time savings. The critical performance properties that the UV-curable coatings were required to meet are defined by the military specification MIL-PRF-85285, "Coating: Polyurethane, Aircraft and Support Equipment."

Initially, two commercial coating suppliers worked to adapt their available coatings to meet these DoD aerospace topcoat requirements. A partnership between Bayer Material Science (BMS) and Deft attempted to adapt low-gloss (also known as "flat") black and gray coatings while DSM Desotech attempted to adapt high gloss, white coatings. DSM Desotech dropped out of the project after its initial effort was unable to achieve a sprayable coating that met other requirements. BMS/Deft reported initial positive results with the flat black and gray coatings, and began an effort to formulate the high gloss, white, UV-curable coating that DSM Desotech was unable to provide.

The BMS/Deft flat coatings proceeded to independent laboratory testing to verify their ability to meet the performance requirements in the project's Joint Test Protocol (JTP). The coatings were also taken to Ogden Air Logistics Center (OO-ALC) for an attempted on-aircraft field demonstration. However, the BMS/Deft flat coatings failed many of the JTP tests, showing extremely inconsistent results. The coatings also failed to achieve successful cure during the attempted demonstration. A recovery plan was developed and enacted to identify the cause of the failures, and BMS/Deft attempted to formulate a new version of the coating to correct the problems. Parallel to these flat coating efforts, the BMS/Deft high gloss coating encountered developmental roadblocks. While most performance criteria were successfully achieved, critical gloss and humidity resistance requirements could not be met. When the new BMS/Deft flat formulations continued to show inconsistent results, both the flat and high gloss BMS/Deft coatings were dropped from the effort.

In order to achieve a UV-curable coating technology suitable for field demonstration, the prime contractor, Concurrent Technologies Corporation (CTC), began a formulation effort based on lessons learned from the previous coating formulation efforts. Based on a survey of commercially available UV-curable resins, this attempt took a "flexibility" approach, making high flexibility, high resistance property resins a priority early in the formulation process. However, at the conclusion of the effort, the flat coatings developed still failed some JTP test requirements and achieved only the minimum requirements on others. An attempted application demonstration at OO-ALC was also unsuccessful.

Without a functional UV-curable coating technology and specific implementation target, a full scale cost analysis could not be conducted. However, information gathered over the course of the effort suggested that opportunity for environmental savings are low due to the increased environmental friendliness of the next generation of isocyanate-cure polyurethane coatings. Labor costs also showed limited opportunity for savings, and the UV lamps necessary to complete cure would require substantial capital investment. UV-curable coatings could potentially reduce maintenance process time, but no specific value for process time reduction was documented during this effort.

The stringent performance requirements of DoD aerospace coatings have proven difficult to meet using UV-curable coatings. Current aerospace topcoats have increased in performance over the past few decades, reaching their current status of high flexibility, high hardness and fluid resistance, low gloss, and long-term resistance to UV degradation allowing aircraft to weather years of direct exposure to sunlight without fading or discoloration. Being able to match not merely the minimum specification requirements, but the best advanced performance of current aerospace coatings would be required for Air Logistics Complexes and aircraft System Program Offices (SPOs) to use UV-curable aerospace coatings.

In addition to needed improvements in performance properties, testing over the course of this project has shown that UV-curable coatings are highly sensitive to a variety of application issues including coating thickness, UV exposure, and compatibility with solvent-based primers. Potential solutions to this include use of an automated paint and cure system to precisely control application and cure. However, the capital investment required for such a system would need to show acceptable payback from process time and material savings. Currently, there is no identified UV-curable coating suitable for implementation.

1.0 INTRODUCTION

1.1 Background

The Department of Defense (DoD) is in the process of transforming and modernizing their depots and maintenance processes with the ultimate goal of reducing the costs and process times associated with programmed depot maintenance activities. One area where the DoD continues to spend millions of dollars annually is painting operations, specifically the use of conventional isocyanate-cure polyurethane and epoxy coatings to protect weapon system substrates. Although these coatings comply with current environmental rules and regulations, their continued use results in the emissions of high volumes of volatile organic compounds (VOCs) and hazardous air pollutants (HAPs). In addition, their use also presents a significant production burden associated with cure times before handling, masking, recoating, or flying. Under ideal conditions, current topcoats cure up to eight hours before stencil markings are applied and 72 hours after application before the aircraft can be flown. Under less than ideal conditions, such as extremes in temperature or humidity, these times can be significantly increased. These long cure times contribute to excessive backlogs in production and reduced airframe availability to the Warfighter.

Ultraviolet- (UV-) curable coatings are a potential alternative to conventional isocyanate-cure polyurethane and epoxy coatings. UV-curable coatings can be manufactured to be HAP and isocyanate-free using only exempt solvents. They are single component, high-solid (nearly 50%), cross-linked coatings that are cured in minutes by exposure to intense UV light. Benefits of successful implementation of UV-curable coatings include:

- Reduced VOC and HAP emissions
- Reduced hazardous waste
- Reduced waste management costs
- Reduced regulatory financial liabilities
- Enhanced environmental leadership role
- Applied using current painting capital equipment [applied through current spray technology, high volume low pressure (HVLP) and traditional coating techniques (i.e., brush, roll or spray)
- Decreased process flow time
- Increased weapon system availability

Concurrent Technologies Corporation (CTC) acted as lead contractor for this project with the Environmental Security Technology Certification Program (ESTCP) to demonstrate/validate (Dem/Val) the capability of selected UV-curable coatings to serve as drop-in replacements for current coating systems used on United States Air Force (USAF), United States Coast Guard (USCG), and United States Navy (USN) aircraft. As UV-curable coatings are not currently in broad use within the aviation community, this project targeted small area aerospace topcoat applications. Ogden Air Logistics Center (OO-ALC) at Hill Air Force Base (AFB) was chosen as the primary demonstration site. Points of contact for this effort are listed in Appendix A, Points of Contact.

1.2 Objectives of the Demonstration

The objective of this effort was to Dem/Val the capability of selected commercially available UV-curable coatings to serve as drop-in replacements for current topcoats and stencil coats used on simple-geometry, on and off-aircraft parts from USAF, USCG, and USN aircraft. The project evaluated selected UV-curable topcoats for their ability to meet or exceed the performance of current coatings, reduce hazardous waste, and reduce process time for depot and field maintenance operations. Upon successful demonstration of a UV-curable topcoat, the objective was to support transition into production use at OO-ALC and potentially other locations. Table 1 summarizes the affected programs and candidate parts where use of UV-curable coatings may help eliminate VOCs and HAPs.

Table 1. Target Hazardous Material (Hazmat) Summary

Target HazMat	Current Process	Applications	Current Specifications	Affected Programs	Candidate Parts and Substrates
VOCs & HAPs (including xylene and ethyl benzene)	Solvent-borne coatings	Aircraft stencil coatings and off-aircraft components	MIL-PRF-85285D	A/OA-10, F-16, C-130, P-3, HH-60, HU-25	**USAF**: F-16 and C-130 markings and repairs; [1]**USN**: P-3 markings and wheels [1]**USCG**: HH-60 exterior panels and fuel tanks

[1] Although USN and USCG aircraft were demonstration targets, the coatings intended for usage with these systems did not pass laboratory testing and were not demonstrated.

1.3 Regulatory Drivers

Large quantities of air emissions are commonly generated by depot painting activities using solvent-borne coatings. In 2006, over eight tons of VOCs were emitted by painting operations at Hill AFB. Many of the substances found in these air emissions are on the Environmental Protection Agency's (EPA's) list of HAPs. In addition, waste from two-component solvent-borne coatings may be as high as 20%, as unused coating cannot be returned to storage after activation.

These emissions and waste products are impacted by a number of regulations promulgated under the Clean Water Act (CWA), Clean Air Act (CAA), and Resource Conservation and Recovery Act (RCRA). Executive Order 34123, dated January 24, 2007, also requires the DoD to reduce the procurement and use of hazardous chemicals and toxic materials. Hazmat reduction is driven by the CAA and RCRA through pollution prevention (P2) efforts. UV-curable topcoats are almost completely free of non-exempt VOCs and HAPs and can be returned to their container for later use if unused in a coating process, allowing an immediate impact on P2 efforts if they can be used in place of current coatings.

2.0 DEMONSTRATION TECHNOLOGY

2.1 Technology Description

The characteristics of the coating technology demonstrated were determined by a number of process requirements. The basic cross-linking chemistry for coatings to cure by exposure to intense UV light was developed and perfected for commercial use in other industries. This base process allows a wide range of variation in the wavelength and intensity of the UV light utilized to cure the coating based on the lamp system used. Safety and environmental concerns determined the UV spectrum used and hence the curing UV lamps utilized as part of this technology. Finally, the specialized performance requirements of coatings used on DoD military aircraft played a large role in determining the final technology characteristics.

2.1.1 Base UV Cure Process

UV-curable coatings are single component, high-solids cross-linked coatings cured by brief exposure to intense UV light. The chemical reaction, or polymerization, that occurs in UV coatings involves three major constituents: photoinitiators, oligomers, and monomers. In the presence of UV light (and dependent on the intensity of the light), photoinitiators absorb specific frequencies of light and initiate a high rate reaction between the oligomers and monomers. Oligomers are polymers that define the coating's physical properties, with examples being urethanes, epoxies, polyester epoxies and acrylates, and polyesters. In UV-coating formulation, the oligomer forms the backbone of the structure and the monomers "link" to the oligomers to form a network during exposure to UV light. Increasing the number of reactive groups, called multifunctional monomers, will increase the cross-linked density of the coating. In addition, these monomers are generally low viscosity and can also serve as a diluent to decrease coating viscosity for application purposes. Figure 1 illustrates the process.

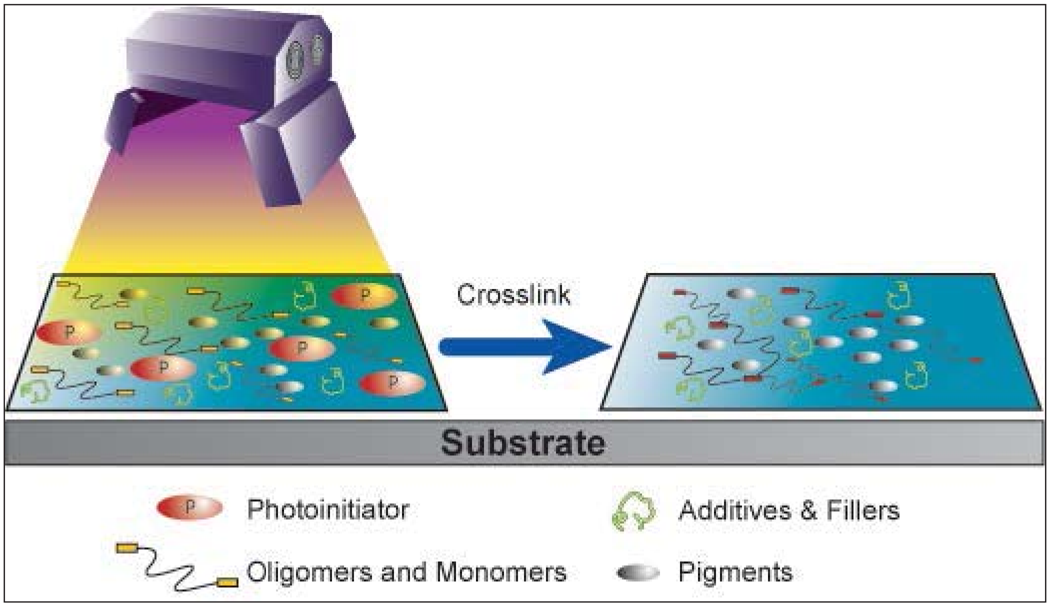

Figure 1. UV Cure Process

UV-curable coatings are commercially available, having been used extensively in Europe for almost 30 years, and have been entering into the United States market within the last 13 years. Primary markets for UV-curable coatings include, but are not limited to, automotive, printing, laminated floor covering, and wood finishing applications. Companies such as Ford, Honda, and BP have been focusing on green technologies and have implemented UV-curable coatings due to its environmental, performance, and operational benefits.

2.1.2 UV Spectrum and Intensity Utilized for Coating Cure

The cure of a UV-curable coating depends on the spectral absorbance peaks of the photoinitiators, the intensity of the UV exposure, and the total energy delivered to the coating being cured. These factors are controlled by the UV illumination source, henceforth referred to as the "UV lamp" utilized with the coating.

Spectral absorption peaks designate the wavelength of the spectrum the photoinitiators can successfully absorb. Successful cure of the coating depends on the energy put out by the UV lamp being in these wavelengths. The wavelengths of the UV light spectrum are divided up into ranges, as shown in Table 2 below.

Table 2. UV Light Ranges

Name	Wavelength in Nanometers (nm)
UVV (visible)	400 nm to 445 nm
UVA (long wave)	315 nm to 400 nm
UVB (medium wave)	280 nm to 315 nm
UVC (short wave)	200 nm to 280 nm

Minimum intensity and total cure energy represent the amount of UV exposure the coating must receive in order to successfully complete cure. Minimum intensity for UV cure is normally expressed in miliwatts per square centimeter (mW/cm^2) or while total energy is typically expressed in terms of milijoules per square centimeter (mJ/cm^2). Thus, the cure illumination requirements of a UV-cure coating can be expressed as a total energy delivered at a minimum intensity at specific spectral absorption peaks. If the energy supplied is less than the minimum intensity required to initiate the cure, the coating will not cure regardless of the total energy supplied over longer periods of time.

Many industrial applications are designed for "full spectrum" UV cure, in which the photoinitiators are designed for cure with high intensity (more than 500 mW/cm^2) UV light with multiple spectral absorption peaks across the UVA, UVB, and UVC spectrums. This combination of longer and shorter wavelengths at high intensities typically allows cure in seconds. However, these full spectrum cures are hazardous to personnel, requiring enclosed cure areas and full protective gear for anyone entering those areas. The hazardous effects of exposure to UV-light result mainly from exposure to the UVB and UVC portion of the spectrum. The American Council Of Government Industrial Hygienists (ACGIH) and National Institute for Occupational Safety and Health (NIOSH) have established the following exposure limit for UVA energy: near UV (315-400 nm): 1 mW/cm^2 for exposures > 16 minutes. Because of the rapid drop-off in power as the distance from the light source is increased, low intensity UVA light sources can safely be utilized in an open body shop environment.

To serve as a drop-in replacement for aerospace coatings utilized on simple-geometry, on and off-aircraft parts and repairs, UV-curable coatings must be applied and cured in the large depot spray booths where full aircraft such as F-16s and C-130s are currently painted during maintenance. This open environment poses a high risk of personnel exposure to direct or indirect UV light. For this reason, all UV-curable coatings utilized in this project were formulated for UVA cure and low intensities.

2.1.3 UV Cure Lamps

In addition to the UVA spectrum and low intensity requirements discussed in Section 2.1.2, the UV lamp systems utilized in this demonstration had to be both portable and explosion-proof. Portability was required to enable the UV lamps to reach various areas of an aircraft and make the technology practical for implementation. The explosion-proof requirement comes from the need for UV lamps to operate within the large spray booths where paint is applied to aircraft.

USAF Technical Order (TO) 1-1-8, “Technical Manual Application and Removal of Organic Coatings, Aerospace and Non-Aerospace Equipment,” states under Section 5-6 Spray Booths and Painting Areas, General: “Lighting shall amply illuminate all surfaces being painted, and all lighting and connecting electrical switching shall be explosion proof.”

Stakeholders in the maintenance wing of OO-ALC, the initial target for implementation of UV-curable coatings, stated that TO 1-1-8 and their own internal operating procedures mandated that any UV lamp utilized for small area repair must be explosion-proof. In this case, explosion-proof is defined as meeting the National Electrical Code (NEC) requirements for Class I, Division I equipment. Based on these requirements, stakeholders determined that successful implementation of UV-curable coatings requires a UVA lamp certified as Class I, Division I under the NEC code and set into a portable manipulation system allowing lamps to be positioned around the aircraft for optimum cure intensities on areas where coating is applied.

There are multiple portable UVA light lamps commercially available which are designed primarily for automotive body shop work. These provide the UVA spectrum, low intensity, and wide cure area required for simple geometry, large and small area coating. During coating optimization and initial rounds of testing according to the Joint Test Protocol (JTP), coatings were cured using a Cure-Tek 1200 Watt lamp system sold by H&S Autoshot, shown in Figure 2. It should not be interpreted that the formulations tested under this project may only be cured specifically with a Cure-Tek system - other UVA lamp systems may be utilized for a successful cure providing they can provide the correct spectral peaks and intensities.

Figure 2. Cure-Tek 1200W Lamp

The Cure-Tek 1200 is a medium-pressure mercury arc lamp technology that produces UV light through the ionization of mercury within a quartz tube. This is accomplished by passing an electrical current across the electrodes located at each end of the tube. Arc lamp technology is a common technology for cure of UV-curable coatings, as it was the first lamp system developed for UV-curing and is still the most widely used technology today. The Cure-Tek 1200 is not explosion-proof in its baseline commercial model. However, during the course of this project a modified Class I, Division I explosion-proof version of the Cure-Tek 1200 was developed by H&S Autoshot. This explosion-proof UVA lamp, shown in Figure 3, was utilized in the final round of laboratory testing and the final depot application demonstration.

Figure 3. Explosion-Proof UVA Lamp

The emission peaks of the Cure-Tek 1200's spectral output across the UV nm range are shown in Figure 4 below. The lines at 315 nm and 400 nm designate the boundaries of the UVA portion of the spectrum. As shown, two large emission peaks of UV energy are at 365 nm and 395 nm, two common absorbance points for commercially available UVA photoinitiators.

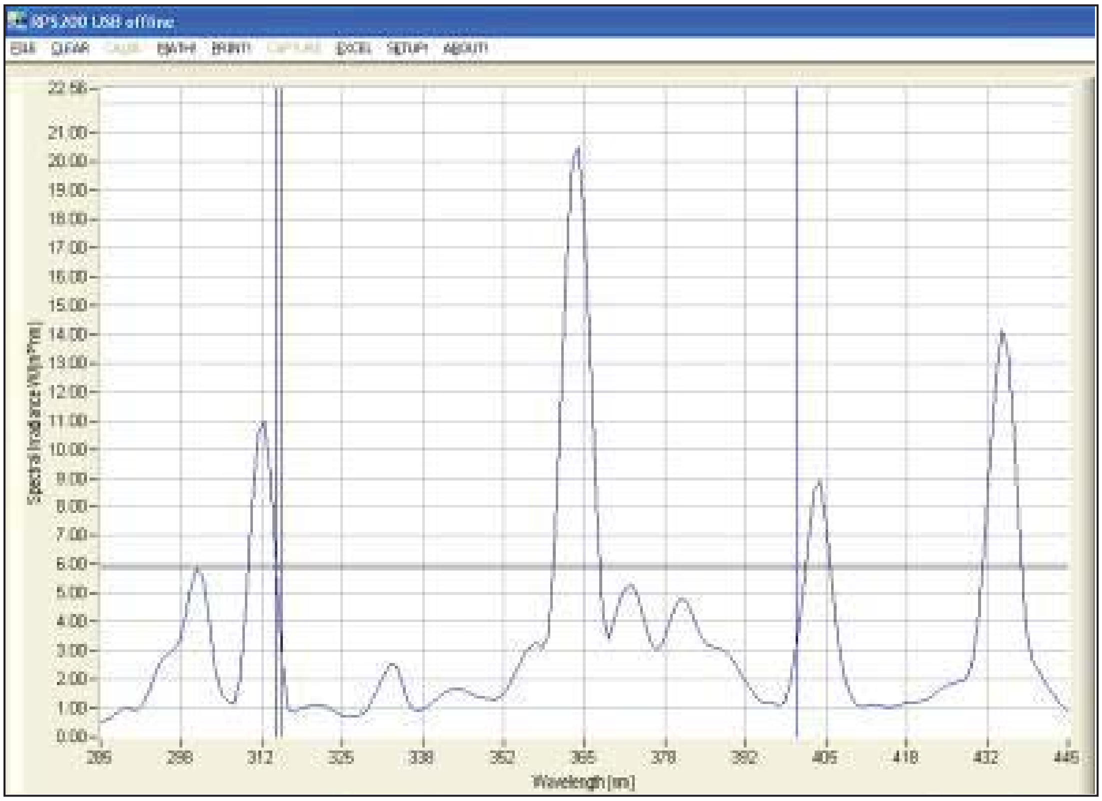

Figure 4. Manufacturer-Provided Spectral Output

Minimum cure intensity requirements varied among the multiple UV-curable topcoats evaluated during this effort, but the final coating demonstrated had a minimum required intensity of approximately 30 mW/cm^2. The minimum cure time at this intensity was determined to be 10 minutes, meaning the minimum required UV energy is approximately 18 J/cm^2. This cure time of 10 minutes is comparatively longer than the full spectrum cure times of seconds utilized in many non-aerospace commercial applications primarily due to the higher thicknesses and pigment and filler loadings of the test coatings. However, a cure time of minutes as opposed to seconds is still desirable over the hours that solvent-borne coatings can take to cure.

2.1.4 Role as Aerospace Coating Drop-In Replacement

Base Coating Stack-Ups

Aircraft substrates may be made of aluminum, steel, other metallic alloys, or non-metallic composite substrates. However, the majority of aircraft surfaces are aluminum, and all testing of the UV-curable coatings was conducted using aluminum substrates.

Similar three-part coating stack-ups are used to paint aircraft for the USAF, USCG, and USN. These consist of a metal pretreatment applied directly to the substrate, a thin layer of primer coating to promote adhesion and provide corrosion resistance, and a topcoat that provides coloration and resistance properties. To create markings, an additional layer of topcoat in a differing color is applied using a stencil. The SPO for most weapon systems require that the primer coating be qualified to the military specification (mil-spec) MIL-PRF-23377 (Primer Coatings: Epoxy, High-Solids) and the topcoats be qualified to MIL-PRF-85285 (Coating: Polyurethane, Aircraft and Support Equipment).

Coatings Targeted for UV-Cure Replacement
This project tested and evaluated UV-curable coatings designed to serve as drop-in replacements for topcoats. There were several reasons for the selection of topcoats as a replacement target. The commercially-available, UV-curable coatings coming closest to meeting mil-spec performance requirements were topcoats. Topcoats are applied to a higher thickness than primer coatings, meaning they are used in higher volume and provide greater potential for environmental savings. Aerospace topcoats can have a cure-to-touch time of 8 hours or more compared to 4 hours or more for primers, meaning that UV-curable topcoats allow for greater process time savings. Topcoats also serve as marking coatings, meaning that they have an immediate implementation opportunity in a low risk, small area application.

Current Cure Times
Current aerospace topcoats qualified to MIL-PRF-85285 are the result of decades of industry development to meet increasing performance requirements. Among other improvements, this has resulted in a reduced “cure-to-touch” time, that is the time after paint is applied before which the paint has not cured enough to risk moving or conducting other work on the aircraft. This is distinct from “cure to fly” which is a longer period after paint is applied before the aircraft can be flown. Where former cure-to-touch times were up to 24 hours, some topcoats qualified under MIL-PRF-85285 cure-to-touch in as little as 8 hours.

Replacing current qualified topcoats with UV-curable coatings that can cure in minutes could save up to 8 hours of cure-to-touch time during which other work cannot be conducted on a part or aircraft.

2.2 Technology Development

2.2.1 Laboratory Screening Testing

The USAF has maintained a long time interest in UV-curable coatings as a means of reducing environmental pollution and maintenance process times. In 2006, the Air Force Research Laboratory (AFRL) established a UV-curable coating program with the goal of testing, demonstrating, and implementing UV-curable coatings for USAF aerospace applications. CTC oversaw this program under the direction of the AFRL. CTC first documented the requirements for quick-cure environmentally-acceptable coatings by conducting site surveys to gather baseline information and performance requirements from the USAF maintenance depots. CTC then conducted a study of the state of the UV-curable coatings technology by submitting a request for information to UV-curable coating vendors and curing technology vendors for interest in pursuing the military aviation market. Based on the results of the market survey, UV-curable coatings with potential for use as aerospace primers, one-coats, topcoats, and primer/topcoat systems were selected for initial screening testing.

This initial screening testing was based on those requirements considered most critical for USAF aerospace coatings per the results of the baseline information from the USAF maintenance depots. These key performance requirements included adhesion, fluid resistance, flexibility, impact resistance, weatherability (for topcoats and one-coats), and corrosion resistance (for primers and one-coats). During the screening testing, 23 coating stack-ups were applied and cured in vendor laboratories under full spectrum UV lights. The USAF's Coatings Technology Integration Office (CTIO) then conducted the screening testing of the selected commercial off-the-shelf (COTS) UV-curable coatings. While none of the COTS coatings tested met all requirements, each performance requirement was met by at least one coating.

As part of the AFRL's UV-curable coatings program, a phased approach was developed to scale up and transition UV-curable coatings into depot maintenance operations. The first phases of this effort were to focus on simple, easy-to-implement applications, leveraging successful implementation of these applications to support further implementations. As described in Section 2.1, a decision was made to focus on UVA-curable aerospace topcoats for simple-geometry, marking coatings, and off-aircraft parts as the first targeted application of the phase approach. This decision was made based on both the results of the screening testing and the feedback from the site surveys. During initial testing, several of the UV-cure coatings tested as topcoats showed strong performance. The site surveys indicated that maintenance depots would be most willing to demonstrate and implement UV-curable topcoats, as primers were considered more critical due to their corrosion prevention properties. Based on the results of the screening testing and the initial site surveys, an ESTCP proposal was submitted. Simultaneously, AFRL directed that a second round of COTS UV-curable testing be initiated. As the enclosed UV-exposure space required for full spectrum cure is considered impractical for small area and marking coatings, it was determined that UVA lamp cure would be required for use in a maintenance environment.

Those UV-cure vendors with topcoats showing promise for aerospace applications were contacted and requested to reformulate their topcoats with the goal of both UVA cure and to better meet USAF aerospace coating requirements. Three suppliers elected to reformulate their topcoats and resubmit for a second round of testing. These were Red Spot Coatings, DSM Desotech, and a partnership of Bayer Material Science (BMS) and Deft coatings. The submitted coatings were tested with two control coatings, one meeting the MIL-PRF-85285 Type I and one meeting advanced performance requirements that would eventually be included in MIL-PRF-

85285 as Type IV, “Aircraft Application with extended weatherability.” In this round of testing, the samples were applied and cured at the CTIO using a Cure-Tek 1200 UVA lamp system. The second round of testing began in March 2008 with the coatings shown in Table 3.

Table 3. Second Round Coatings

Vendor	Color	Identifier
Control meeting MIL-PRF-85285	Camo Gray	Deft 03-GY-321
Control meeting APC	Camo Gray	Deft 99-GY-001
BMS/Deft Coatings	Camo Black	21BK001
BMS	Camo Black	NB 954148
BMS	Camo Black	NB 954149
BMS	Camo Black	NB 954150
Red Spot	Gloss White	UVX0724
DSM Desotech	Gloss White	DN-0197
DSM Desotech	Camo Gray	DN-0196
Red Spot	Camo Gray	UVX0726

These coatings underwent testing based on the MIL-PRF-85285 requirements, and the resulting data was analyzed. Full data is shown in Appendix B, Second Round Test Data. To summarize, the BMS/Deft coating, 21BK001, showed excellent performance properties in nearly all requirements, falling short only in gloss requirements and impact resistance. For gloss coatings, the DSM gloss white coating showed good resistance to fluids and nearly met requirements for color change in the UV weathering chamber. The Red Spot gloss white was unable to meet minimum adhesion requirements, adhesion being the most important requirement for any coating.

2.2.2 Field Trial of 21BK001

Per AFRL direction, CTC supported an ongoing effort by the CTIO to conduct field trials of the 21BK001 for marking applications. CTC monitored two field demonstrations where these topcoats were applied as markings on DoD aircraft. The first field demonstration was conducted at the Iowa Air National Guard on December 11, 2007. The black 21BK001 and an experimental gray version were applied by representatives from BMS and Deft Coatings as stenciled markings on the tail of an Iowa Air National Guard F-16 aircraft in Des Moines, Iowa. The flat black coating was successfully applied and cured with a Cure-Tek 1200 lamp system. However, the gray coating could not be cured and was removed. Later investigation indicated that the coating failure may have been due to a formulation error. Figure 5 shows the cure in progress.

Figure 5. Field Trial on Iowa Air National guard F-16

A second field trial was conducted at the USAF Reserve's 911th Airlift Wing at Pittsburgh, Pennsylvania on April 18, 2008. A flat black marking coating was stenciled on the unit designator and wing flap of a C-130 aircraft. As before, the coating was applied and cured successfully. These demonstrations provided useful practical field experience for the USAF's ongoing UV-curable coatings program. Figures 6 and 7 show the coating being cured on the wing flap and unit designator.

Figure 6. Black Topcoat Cured on 911th Airlift Wing C-130 Wing Flap at Pittsburgh 911th USAF Reserve

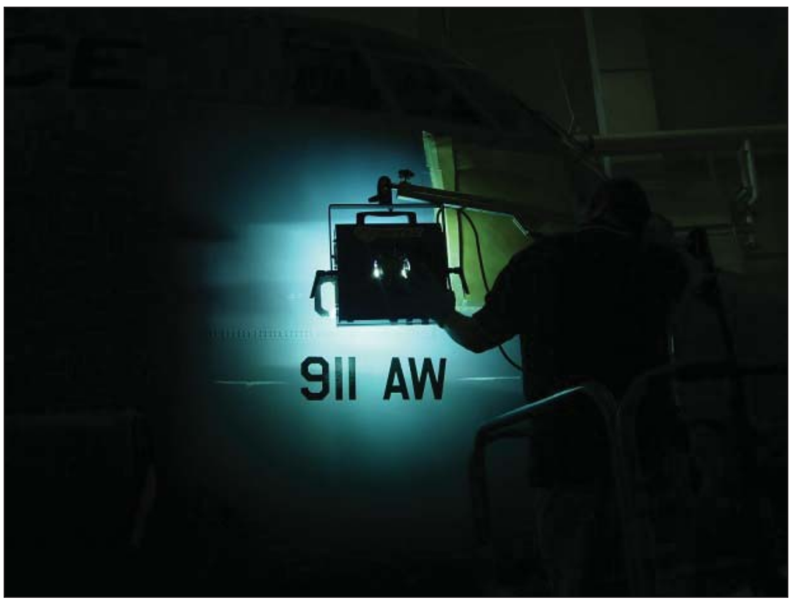

Figure 7. Black Topcoat Cured on C-130 Unit Designator at Pittsburgh 911th USAF Reserve

2.2.3 Final Selection for ESTCP

Most aircraft topcoats used in high quantities across the USAF, USCG, and USN are various shades of gray, white, and black (though the USCG also uses orange coatings). The most commonly used gray and black colors are low gloss, also known as “flat” or “camo.” The most commonly used white colors are high gloss, generally known as “gloss.” Discussion with UV coating vendors indicated that flat and gloss coatings pose different types of formulation challenges and would have to be developed separately. Based on the screening test results, BMS/Deft was selected to conduct reformulation and optimization of flat black and gray coatings based on 21BK001. DSM Desotech was to conduct reformulation and optimization of gloss white coatings based on DN-0197. The selected color/gloss combinations, noted in Table 4, were chosen based on their applicability to demonstration and technology transition targets.

Table 4. UV-Cure Coatings Targeted for Development

Color	FED-STD-595C Color Number	Supplier	Usage
Camo Gray	36118	BMS/Deft	F-16 markings
Camo Gray	36173	BMS/Deft	C-130, KC-135 exterior topcoat
Flat Black	37038	BMS/Deft	Aircraft markings (multiple systems)
Gloss White	17860	DSM Desotech	Aircraft parts / markings for USCG
Gloss White	17925	DSM Desotech	Aircraft parts /markings for USAF and USN

2.3 Advantages and Limitations of the Technology

UV-curable coatings offer the following benefits over current solvent-borne isocyanate-cure polyurethane coating systems:

- Reduction/elimination of VOC and HAP emissions
- Fully cured within minutes of UV exposure, decreasing dry-to-touch and dry-to-fly time, which increases mission readiness
- Requires less paint due to being a one component system with no wastage due to over preparation
- Does not have pot life issues associated with multi-component solvent- or water-borne conventional coatings

UV-curable coatings have the following limitations compared to current use solvent-borne coating systems:

- Additional capital investment, operation, and maintenance budget required for UV lamp system
- Exposure to UV light can be a worker safety issue

- High sensitivity to application thickness, as too-thick coating application can prevent successful cure
- Additional labor required to operate and direct UV-cure system
- Direct exposure of coating to UV light required for successful cure, making cure of complex three dimensional geometries difficult

Of these limitations, the first four are expected to be persistent trade-offs for the use of UV-curable coating technology, although automating the application and cure process is expected to provide mitigation. It is expected that the difficulties of curing complex surfaces will be addressed through continuing technological developments such as dual-cure coatings that will slowly cure areas missed by UV exposure and robotic UV lamps systems that are programmed to fully expose the entire coated substrate.

3.0 PERFORMANCE OBJECTIVES

Performance objectives consisted of two categories. The first is laboratory performance objectives as required by the JTP. The second set of performance requirements evaluated during field application demonstrations of the UV-curable coatings.

3.1 JTP Performance Objectives

The JTP was prepared to delineate and describe the laboratory testing required to validate COTS UV-curable coatings for DoD aerospace topcoat applications. These minimum acceptable performance requirements were drawn directly from the mil-spec MIL-PRF-85285D. UV-curable coatings cannot qualify under the MIL-PRF-85285 mil-spec due to composition requirements mandating usage of pigmented polyester resins and aliphatic isocyanate resins. However, there is precedent for weapon system SPO authorizing use of coatings meeting performance requirements without official qualification to the specification.

There is one important note regarding these objectives. While the JTP performance objectives represent performance requirement for on-aircraft usage MIL-PRF-85285 Types I and III,[1] the February 2, 2009 revision to MIL-PRF-85285 introduced a new Type IV “Aircraft Application with Extended Weatherability.” Over the time period of this project, Type IV has been adopted as standard for the majority of USAF aircraft. Type IV has a 3000 hour requirement to maintain color and gloss during accelerated weathering testing, as compared to the 500 hour requirement of other MIL-PRF-85285 types. Aircraft painted with Type IV coating may potentially go longer between repaints while still maintaining professional military appearance. While UV-curable coatings that do not meet the 3000 hour requirement could still be used in marking and repair applications, stakeholders in the USAF, USN, and USCG have indicated that UV-curable topcoats used over large areas of an aircraft surface would need to meet the Type IV requirements.

Multiple iterations of JTP testing were conducted for UV-curable coatings, as the initial reformulated coatings from BMS/Deft and DSM Desotech failed to meet performance objectives. Table 5 presents a brief summary of the JTP requirements and results for the final 36173 gray and 36118 gray UV-curable coating colors tested. (Gloss white and flat black formulations dropped out of testing before the final test iteration.) More detail on all iterations of JTP testing will be presented in Section 6.

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[1] Type II is for ground support equipment.

Table 5. JTP Performance Requirements

Tests	ASTM Standards	Target Criteria	Results 36118 Gray	Results 361173 Gray
Color	D 2244	Color difference (ΔE) of less than 1 from standard	Pass	Pass
Gloss	D 523	At 60° ≤ 5; at 85° ≤ 9	Pass	Pass
Wet Tape	D 3359, Method A	No peel away; target rating of 4A or 5A	4A	4A
MEK Rub	None	No substrate exposure	Pass	Pass
Low Temp. Bend	D 522	No cracking or adhesion loss over 1 inch bend (gloss and semi-gloss) or 2 inch bend (flat)	Pass	Pass
GE Impact	D 6905	Minimum of 40% elongation; no cracking, crazing, or loss of adhesion	40%	40%
Pencil Hardness	D 3363	HB or harder; initial hardness - data point for fluid resistance	F (Pass)	F (Pass)
Fluid Resistance (Lube oil, hydraulic fluid, JP-8 fuel)	D 3363 D 3359	Softening no more than two (2) pencil hardness unit; no blistering or defects after exposure to lube oil, hydraulic fluid and JP-8 fuel	Pass	Pass
Accelerated Weathering (Color and Gloss)	G 155	Color change (ΔE) of less than 1 after 500 hours; five (5) gloss	**Fail**	**Fail**
Heat Resistance	D 2244	Color change (ΔE) of less than 1 after exposure to 250 ± 5ºF for 60 minutes	**Fail**	Pass
Humidity Resistance	D 2247	No blistering, softening, loss of adhesion or other film defects	Pass	Pass
Cleanability	D 2244	Cleaning Efficiency ≥ 75%	Pass	Pass

No formulation of the UV-curable coatings was able to successfully pass all JTP performance requirements despite repeated development and testing iteration cycles and assistance sought from multiple coating developers. Without the ability to meet these performance requirements, the coatings could not proceed to a full scale demonstration or eventual implementation. Note that while the accelerated weathering and heat resistance results were the failure points for the final test iteration, various iterations of UV-curable formulations passed accelerated weathering but failed on other objectives such as GE impact flexibility or fluid resistance. As noted in

Section 2.2.1, the Deft/BMS 21BK001 evaluated during screening testing failed only in meeting minimum gloss requirements and GE impact resistance flexibility.

3.2 Field Demonstration Performance Objectives

Per the Demonstration Plan, UV-curable topcoats that meet JTP performance objectives were to proceed to a one year on-aircraft field demonstration. Since none of the coating formulations successfully passed the JTP testing iterations, the one year on-aircraft test was not conducted. Two attempts were made to conduct an on-site application and cure trial at OO-ALC as a partial demonstration under depot maintenance conditions. One application demonstration was attempted on July 13-15, 2010, and the second demonstration was attempted on June 12, 2012. In both demonstrations, attempts to successfully cure the UV-curable coatings failed. Results of these demonstrations are detailed more fully in Section 6.

Due to these depot application failures and inability to conduct a one-year field evaluation, most of the field demonstration performance objectives could not be evaluated. Table 6 shows field demonstration performance objectives listed in the Demonstration Plan and the results where applicable.

Table 6. Field Demonstration Performance Objectives

Performance Objective	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives			
Pollution Prevention Savings	• Record quantities of UV-curable coatings used and solvent-borne coatings used for targeted components • Record VOC and HAP content of UV-curable and solvent-borne coatings	Show reduction in air emissions from current coating systems	Formulation shows fewer pollutants, but without implementation savings cannot be estimated
Color/Gloss change over one year	• Record initial post-cure color/gloss for UV-curable coatings and control coatings for each aircraft • Take color/gloss readings at six month intervals for one year	Show color/gloss ΔE of ≤ 1 OR color gloss $\Delta E \leq$ that of the control coating	Not tested
Process Time Reduction	• Track total time required to complete coating application and full UV-cure • Track total time required for cure-to-flight with current coating system	Show reduction in process time from that of current process	Not tested
Qualitative Performance Objectives			
Coating ease of application	Feedback from facility personnel on ease of applying UV-curable coating; thickness of applied coating	Facility personnel indicate minimal to no increase in difficulty from current coatings; thickness of applied coating matches current systems	Some trials and multiple attempts required to learn how to spray coating to correct thickness
Coating appearance	Take visual observations and photographs of UV-cured and control coatings immediately after cure and at six month intervals	Appearance of coating matches that of current coating	Not tested

Though most field performance objectives cannot be evaluated, Table 7 shows a comparison can be made between the pollutant content of the final UV-curable topcoat formulations and Defthane Extended Lift Topcoat (ELT) 36173 Gray Color, a topcoat supplied by Deft Coatings that meets MIL-PRF-85285, Type I.

Table 7. Pollutant Comparison

Pollutants	UV-Curable Formulations	Defthane ELT 36173 Gray
VOCs	Utilize only exempt[1] solvents	15-40% by weight
HAPs	None	3-7% by weight (xylene)

[1]Exempt solvents do not react with sunlight to form smog, so their use is thus free of legislative control.

4.0 SITES/PLATFORM DESCRIPTION

4.1 Test Facilities and Weapon Systems

In the approved Demonstration Plan, three sites were selected for field demonstration of UV-curable topcoats. Due to the inability of UV-curable formulations to pass laboratory performance testing, limited application trials were conducted only at the primary demonstration site, OO-ALC at Hill AFB.

Hill AFB is an Air Force Materiel Command base located near Layton, Utah. Hill is home to many operational and support missions. Hill AFB is the site of OO-ALC, one of the USAF's three maintenance depots. The base performs depot maintenance on the F-16, A-10 and C-130 aircraft. Two Principal Investigators (PIs), both located at OO-ALC, oversaw this ESTCP program. They were Mr. Glen Baker and Mr. John Jusko. Mr. Baker was lead of process engineering for Aircraft Coatings Application & Removal at Hill AFB. Mr. Jusko, who took over from Mr. Baker in July 2010, is the Local Small Business Innovation Research (SBIR) Program Manager.

The selected demonstration targets were F-16 aircraft markings and C-130 markings and small surfaces such as propeller tips, engine exhaust tracks, life raft covers, and escape hatch covers. Potentially off-aircraft components from the F-16 and/or C-130 or A-10 would also have been included. Hill processed 128 F-16 aircraft, shown in Figure 8 below, in 2007. The F-16 markings were chosen as a demonstration target for several reasons. First, the quantity processed per year nearly guaranteed availability for field demonstration as well as providing a high benefit if current stencil coatings can be replaced with UV-curable coatings. Additionally, USAF F-16 aircraft markings are painted with Camo Gray 36118, which is also used as topcoat on USAF B-52 and HH-60 aircraft. A successful demonstration of the Camo Gray 36118 as a stencil coating would have potentially led to later implementation as a topcoat on B-52 and HH-60 aircraft.

Figure 8. USAF F-16 Aircraft

Hill processed 43 C-130 aircraft, shown in Figure 9, in 2007. C-130 markings are painted with Camo Black 37038, which is widely used in stenciling and other applications throughout the USAF, USN, and USCG. In addition to markings, the C-130 has convenient hatch covers for demonstrating the Camo Gray 36173 UV-curable formulation. Because Camo Gray 36173 is used as a topcoat on USAF C-130, C-5, C-17, and KC-135 aircraft, successful demonstration of the coating on small exterior aircraft areas would have potentially led to further implementation opportunities.

Figure 9. USAF C-130 Aircraft

However, as discussed in Section 3, multiple iterations of the UV-curable topcoats failed to meet laboratory performance requirements. Application demonstrations were conducted at OO-ALC on a simulated aircraft surface, pictured in Figure 10, but no UV-curable coatings were applied to in-service aircraft or components.

Figure 10. Simulated Aircraft Surface Used in Application Demonstration

4.2 Present Operations

In terms of overall process, the targeted painting operations are similar throughout all DoD aircraft maintenance activities. The targeted application types are stencil markings, where the UV-curable coating is applied over a solvent-borne topcoat, repairs where a small area of the aircraft surface is repainted with UV-curable coating after being stripped for repair, and off-aircraft painting where a component removed from the aircraft during the maintenance process is coated with the UV-curable coating as a topcoat. All UV-curable coatings utilized in this demonstration have equal applicability for either application. Figure 11 shows the depot painting operation for aircraft. Off-aircraft components have primer and topcoat applied in separate painting areas.

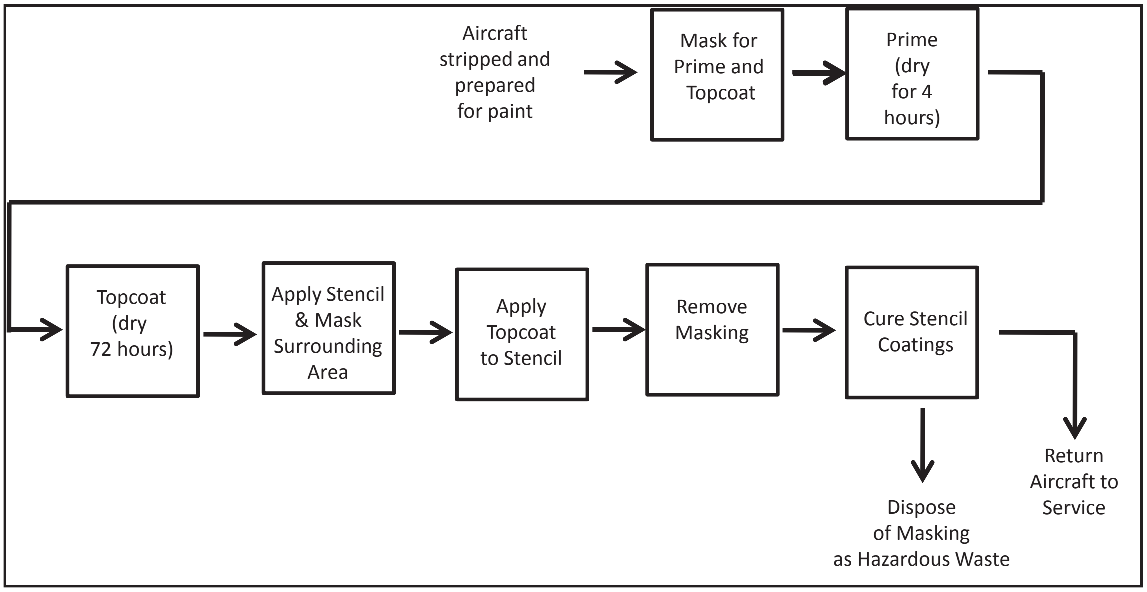


Figure 11. Current Depot Painting Flow Chart

4.3 Site-Related Permits and Regulations

The UV-curable coatings application demonstration required that two items be brought on site. These items were: 1) liquid samples of the UV-curable coating colors being demonstrated and 2) the UV curing lamp system. As discussed in Section 2.1.3, Environmental, Health, and Safety (EH&S) personnel determined that a UV lamp implemented in the aircraft paint area would have to be Class I, Division I explosion-proof by NEC standards. An explosion-proof version of the UV lamp was procured under a related effort for use in this project, and similar explosion-proof systems would likely be required for any UV-curable coating implementation conducted in aircraft paint areas at DoD installations.

A Materials Data Safety Sheet (MSDS) for each demonstrated UV-curable coating was submitted to the EH&S office at OO-ALC prior to each application demonstration. The MSDSs were reviewed and the demonstrations were approved.

5.0 TEST DESIGN

Three forms of testing were carried out during this effort. During internal development testing, coating development teams attempted to reformulate their coatings to meet performance requirements. This testing occurred on a less structured, development basis as various performance properties were tested and retested as the coating formulation changed. Once these development teams indicated that their coatings would pass aerospace performance requirements, the coatings were submitted to structured laboratory testing according to the JTP. In addition, application trials were performed to document the ability of the coatings to be applied and successfully cured.

5.1 Internal Development Testing

Internal development testing occurred outside the scope of the JTP but prior to the field demonstrations. Coating developers carried out internal testing during their optimization work on the flat grays and black and the gloss white formulations. The design and performance objectives of these tests are fully described under Section 5.2, JTP testing. This section will describe which development team carried out internal developmental testing on which formulations. Table 8 summarizes this information.

Table 8. Summary of Internal Development Testing

Development Team	Coatings	Testing
DSM Desotech	• Developmental gloss white based on DN-0197	• Gloss • Adhesion • Weathering • GE Impact Flexibility • Heat resistance • Opacity • Fluid resistance
BMS / Deft Coatings	• Developmental 36173 Gray Coating (21GY001) • Developmental 36118 Gray Coating (21GY002) • Developmental 37038 Black Coating (21BK003)	• Color/Gloss • Adhesion • Weathering (500 hrs) • Flexibility • Fluid resistance • Heat/humidity resistance • Opacity • Freeze/thaw • Cure thickness
	• Developmental waterborne gloss white (BMS #096098)	• Color/Gloss • Adhesion • Weathering (500 hrs) • Flexibility • Fluid resistance • Heat/humidity resistance
CTC / BBM Technologies	• Developmental flexible resin based 36173 Gray Coating • Developmental flexible resin based 36118 Gray Coating • Developmental flexible resin based Black Coating	• Color/Gloss • Adhesion • Weathering (500 hrs) • Flexibility • Fluid resistance • Heat/humidity resistance

5.1.1 DSM Desotech Internal Development

DSM Desotech (DSM) is a developer of formulated coatings and composites who entered the UV-curable market through development of UV-curable optical fiber materials. Based on the results of the screening testing described Section 2.1.2, DSM was subcontracted to formulate gloss white coatings meeting aerospace requirements. The intent was that DSM would serve as a supplier for UV-curable aerospace topcoats upon completion of the effort. This laboratory work was conducted through their "UVention" group dedicated to the development of specialty UV-curable coatings. Address and contact information for UVention is listed below:

John K. Braddock
DSM Desotech Inc.
1122 St. Charles Street
Elgin, Illinois 60120-8498 USA
Tel: +1-224-402-0924
UVention™: (within the USA) 1-866-491-2197
Fax: +1-732-745-7468
John.braddock@dsm.com
www.Uvention.com

Developmental formulation and testing occurred at DSM from February 17, 2009 until direction to stop work on September 7, 2009. Work was conducted using a Cure-Tek 400W unit, a smaller laboratory scale version of the Cure-Tek 1200W. Stop work direction was issued after determination that DSM Desotech did not see a viable path to achieving coatings meeting DoD aerospace requirements based on internal test results. The results of developmental testing conducted during this period are reported in Section 6.

5.1.2 BMS/Deft Coatings Flat Coating Internal Development

Bayer Material Science is a supplier of UV-curing resins, and Deft Coatings is an aerospace coatings supplier who sells topcoats qualified to MIL-PRF-85285 in a variety of colors and types. Based on the results of the screening testing described in Section 2.1.2, BMS was subcontracted to partner with Deft Coatings for the formulation of flat black and gray coatings meeting aerospace requirements. The intent was that Deft Coatings would serve as a supplier for UV-curable aerospace topcoats upon completion of the effort. Address and contact information for BMS and Deft Coatings are listed below:

Mike Gallagher
Director, Government Services Group
Bayer Material Science LLC
100 Bayer Rd.
Pittsburgh, PA 15205 USA
Office Phone: 412-777-4833
Mobile: 330-204-1334

Randy Brady
Marketing Director of Military & Entertainment
17451 Von Karman Avenue
Irvine , CA 92614 USA
www.deftfinishes.com
Phone: 1-949-474-0400

Developmental formulation and testing began at BMS and was transferred to Deft Coatings after substantial completion of the formulation. These activities continued from February 2009 through December 2010. Work was initially conducted using a Cure-Tek 400W unit, but the development team at Deft Coatings switched to use of a Cure-Tek 1200. The results of developmental testing conducted during this period are reported in Section 6.

In January 2010, the resultant coatings were submitted for JTP testing at Battelle Memorial Laboratories, and in July 2010 an attempt was made to conduct an on-aircraft demonstration at OO-ALC. As described in Section 6, both the JTP testing and the attempted demonstration resulted in coating failures. From July 2010 through December 2010, Deft Coatings attempted recovery testing to identify and correct the source of the failures. These tests and results are reported in Section 6.

5.1.3 BMS/Deft Coatings Gloss White Coating Internal Development

Upon determination that DSM Desotech gloss white coating would be unable to satisfy requirements, CTC sought an alternate source for UV-curable gloss white coatings which could meet USAF, USN, and USCG needs. In late 2009 the BMS/Deft partnership proposed an effort to formulate UV-curable coatings meeting aerospace requirements that would satisfy the gloss white requirements for FED-STD-595C 17860 and 17925. This proposal was largely based around using waterborne UV curable polyurethane dispersions (UV-PUD) as the basis for the coating rather than the oligomeric UV-curable coatings used as a basis for the flat black and grays. Because BMS would be using an off-the-shelf UV-PUD as the basis for the formulation, the proposal was to complete formulation within a year.

Work began on January 13, 2010 and continued through December 15, 2010, when a stop-work order was issued to BMS based on an inability to meet gloss and humidity resistance requirements. The internal development tests over this time period are reported in Section 6.

5.1.4 CTC/BBM Technologies Coating Internal Development

Upon determination that neither the flat nor the gloss BMS/Deft coatings would meet requirements, a meeting was conducted with the PI at OO-ALC on January 25, 2011, to determine if a viable path existed to achieving UV-curable coatings. The proposed solution was that CTC work directly with a new coatings formulator, BBM Technologies, to attempt to create a UV-curable coating meeting MIL-PRF-85285 performance requirements. BBM technologies had extensive experience with creating specialty coatings for the USAF. Combined with internal UV-curing expertise, the proposed approach was to evaluate commercially available UV-cure resins and select the most flexible resins as the basis for the new coating.

The rationale for this “flexibility approach” was as follows:

- UV-curable aerospace coatings previously developed had not met flexibility requirements, and experience suggested that increasing coating flexibility causes other properties to suffer
- Addition of fillers and pigments decrease flexibility
- Effort focused upon identifying extremely elastomeric resin
- Resin needed to be flexible yet tough
- Pencil hardness used as quick indicator of resistance properties in screening testing

The PI and stakeholders at OO-ALC agreed to this revised approach, and the effort was conducted from February 2011 through February 2012. The coatings entered testing at CTC's Johnstown, Pennsylvania facility in February 2012. Results of developmental performance testing are reported in Section 6.

5.2 JTP Testing

The following sections list the materials, test procedures, and test requirements for the JTP testing that was conducted. Test procedures previously referenced during developmental testing can be assumed to be identical.

Note that JTP testing includes 'Minimum Performance Criteria,' based on the requirements of MIL-PRF-85285 Type I and 'Optimum Performance Criteria,' based on the requirements of Advanced Performance Coating system specification, MIL-PRF-32239. The requirements of MIL-PRF-32239 are comparable to those of MIL-PRF-85285, Type IV and include the extended 3000 hour artificial weathering resistance requirement. The first coatings to enter JTP testing, the flat black and grays developed by BMS/Deft, were tested to both minimum and optimum requirements. However developmental testing under the CTC/BBM effort showed that it would be impossible for those coatings to meet optimum requirements. Therefore they were tested only to the Minimum Performance Criteria developed from MIL-PRF-85285 Type I. Certain other tests were omitted due to limited schedule and funding availability by the time CTC/BBM coating was ready to proceed to testing. These tests will be noted where applicable.

5.2.1 Materials and Coating Application

All coatings were cured per instructions provided by the development team. All coatings were applied using a HVLP spray system. The sample sizes, processing requirements, post-treatment, and cutting methodology utilized during testing are discussed in the following sections.

5.2.1.1 Test Specimen Fabrication

All test specimens were fabricated from either 2024-O temper or 2024-T3 temper aluminum. All 2024-O anodized panels were bare (unclad) and utilized for all flexibility testing (i.e., impact and low temperature) as noted in applicable *Test Methodology Sections*, while the 2024-T3 bare (unclad) panels were utilized for all other testing activities. Upon completion of fabrication, the test panels were labeled with specific identification markings used to facilitate the tracking of coating test results. Panel sizes were 3”x 6” except for the reparability testing (reparability panels were 12” x 12” 2024-T3 bare).

Each test specimen/panel was given a pre-treatment prior to coating application. The 2024-T3 panels were treated with a conversion coating conforming to MIL-C-5541, class 1A; while the 2024-O panels were treated with chromic acid anodize in accordance to MIL-A-8625, Type 1.

Test specimens coating stack-ups were applied according to one of ten (10) processing scenarios:

1) *Fed-STD-595C 36173 Flat Gray Minimum Performance Control*:
    a. MIL-PRF-85285D Type I qualified, flat gray 36173 solvent-borne topcoat over
    b. MIL-PRF-23377 Type I Class C2 primer on
    c. unclad aluminum 2024-T3 substrate treated with a conversion coating conforming to MIL-C-5541, class 1A

2) *Fed-STD-595C 36118 Flat Gray Minimum Performance Control*:
    a. MIL-PRF-85285D Type I qualified, flat gray 36173 solvent-borne topcoat over
    b. MIL-PRF-23377 Type I Class C2 primer on
    c. unclad aluminum 2024-T3 substrate treated with a conversion coating conforming to MIL-C-5541, class 1A

3) *Fed-STD-595C 37038 Flat Black Minimum Performance Control*:
    a. MIL-PRF-85285D Type I qualified, flat black 37308 solvent-borne topcoat over
    b. MIL-PRF-23377 Type I Class C2 primer on
    c. unclad aluminum 2024-T3 substrate treated with a conversion coating conforming to MIL-C-5541, class 1A

4) *Fed-STD-595C 36173 Flat Gray Optimum Performance Control*:
    a. MIL-PRF-85285 Advanced Performance Coating (APC) Type IV flat gray 36173 topcoat over
    b. MIL-PRF-23377 Type I Class C2 primer on
    c. unclad aluminum 2024-T3 substrate treated with a conversion coating conforming to MIL-C-5541, class 1A

5) *UV-cure Coating Performance Specimen (per UV-cure coating tested)*:
    a. Candidate UV-cured topcoat over
    b. MIL-PRF-23377 Type I Class C2 primer on
    c. unclad aluminum 2024-T3 substrate treated with a conversion coating conforming to MIL-C-5541, class 1A

6) *Fed-STD-595C 36118 Flat Gray Minimum Flexibility Control*
    a. MIL-PRF-85285D Type I qualified, flat gray 36173 solvent-borne topcoat on
    b. unclad aluminum 2024-O, chromic acid anodized in accordance to MIL-A-8625, Type 1 (no primer)

7) *Fed-STD-595C 36173 Flat Gray Minimum Flexibility Control*
    a. MIL-PRF-85285D Type I qualified, flat gray 36173 solvent-borne topcoat on
    b. unclad aluminum 2024-O, chromic acid anodized in accordance to MIL-A-8625, Type 1 (no primer)

8) *Fed-STD-595C 37308 Flat Black Minimum Flexibility Control*
    a. MIL-PRF-85285D Type I qualified, flat black 37308 solvent-borne topcoat on
    b. unclad aluminum 2024-O, chromic acid anodized in accordance to MIL-A-8625, Type 1 (no primer)

9) *Fed-STD-595C 36173 Flat Gray Optimum Flexibility Control*
    a. MIL-PRF-85285 APC Type IV flat gray 36173 topcoat on
    b. unclad aluminum 2024-O, chromic acid anodized in accordance to MIL-A-8625, Type 1 (no primer)

10) *UV-cure Coating Flexibility Specimen (per UV-cure coating tested)*:
    a. Candidate UV-cured topcoat on
    b. unclad aluminum 2024-O, chromic acid anodized in accordance to MIL-A-8625, Type 1 (no primer)

5.2.2 TESTING REQUIREMENTS

All testing was conducted in accordance with the documents referenced in Table 9 unless otherwise noted in the individual test paragraph. If a deviation is made from the reference document, then the variance will be noted in the specific test paragraph.

Table 9. JTP Test Requirements Summary

Engineering Requirement			
Tests	**ASTM**	**Minimum Performance Target Criteria**	**Optimum Performance Target Criteria**
Appearance			
Color	D 2244	Color difference (ΔE) of less than 1	Same.
Gloss	D 523	At 60°: ≥90 for gloss; ≤5 for flat; (Flat must also be ≤9 at 85°)	Same.
Dry Film Thickness	D 7091	Primer: 0.6- 0.9 mils Topcoat: 1.7- 2.3 mils	Same.
Adhesion			
Wet Tape	D 3359, Method A	No peel away; target rating of 4A or 5A	Same.
Cross Hatch	D 3359, Method B	None.	No peel away; target rating of 4B or 5B
MEK Rub	None	No substrate exposure	Same.
Stencil Coat Adhesion	D 3359, Method A	No peel away; target rating of 4A or 5A	Same.
Hot/Cool and Humid/Dry Cure Conditions	D 3359, Method A and B	None.	No peel away; target rating of 4A or 5A and 4B or 5B.
Flexibility			
Low Temperature	D 522	No cracking or adhesion loss over 1 inch bend (gloss) or 2 inch bend (flat)	No cracking or adhesion loss over 1 inch bend (gloss) or 2 inch bend (flat) before and after weathering
GE Impact	D 6905	Minimum of 40% elongation; no cracking, crazing, or loss of adhesion	Minimum 60% elongation for gloss and 40% for flat before weathering; Minimum 40% elongation for gloss and 20% for flat after weathering
Resistance			
Pencil Hardness	D 3363	HB or harder; initial hardness - data point for fluid resistance	Same.
Fluid Resistance (Lube oil, hydraulic fluid, Skydrol, JP-8 fuel, deionized water)	D 3363 D 3359	Softening no more than two (2) pencil hardness unit; no blistering or defects after exposure to lube oil, hydraulic fluid and JP-8 fuel	No blistering, coating delamination, adhesion loss or 2 pencil hardness change after exposure and colorΔE ≤ 3 after exposure to Lube oil, hydraulic fluid, Skydrol, JP-8 fuel, deionized water.

Table 9. JTP test Requirements Summary (Continued)

Engineering Requirement			
Tests	**ASTM**	**Minimum Performance Target Criteria**	**Optimum Performance Target Criteria**
Resistance			
Accelerated Weathering (Color and Gloss)	G 155	Color change (ΔE) of less than 1 after 500 hours; Minimum gloss of 90 for gloss; Minimum 15 for semi-gloss; maximum five (5) for flat	Color change (ΔE) of less than 1 after 3000 hours; Minimum 90 for gloss; Minimum 15 for semi-gloss; maximum (5) for flat
Heat Resistance	D 2244	Color change (ΔE) of less than 1 after exposure to 250 ± 5ºF for 60 minutes	Color change (ΔE) of less than 1 after exposure to 350 ± 5 ºF for four (4) hours. No cracking or adhesion loss over 1 inch bend (gloss and semi-gloss) or 2 inch bend (flat) and after high temperature exposure
Humidity Resistance	D 2247	No blistering, softening, loss of adhesion or other defects.	Same.
Cleanability	D 2244	Cleaning Efficiency ≥ 75%	Same.
Salt Spray	B 117	None.	No blisters or undercutting from the scribe; no discoloration in the scribe and no pitting in the scribe
Reparability			
Scuff sand and overcoat Wet Tape	D 3359, Method A	No peel away; target rating of 4A or 5A	Same.
Scuff sand and overcoat Cross Hatch	D 3359, Method B	No peel away; target rating of 4B or 5B	Same.
Stripability			
Chemical Strippers	None.	None.	Removal of the coating to the substrate
Dry Media (blasting)	None.	None.	Removal of the coating to the substrate
Laser	None.	None	Removal of the coating to the substrate

5.2.3 TEST DESCRIPTIONS

Performance requirements and test methods are defined in this section. Specific test descriptions, rationales and methodologies are described along with any major or unique equipment or instrumentation utilized for testing. The test methodology includes the definition of test parameters and conditions and acceptance criteria. The test methods represent acceptable procedures to define a performance requirement or to differentiate performance characteristics between different coatings.

5.2.3.1 Appearance Tests

5.2.3.1.1 Color

Test Description

The test was conducted in accordance with ASTM D 2244, *Standard Practice Calculation of Color Tolerances and Color Differences from Instrumentally Measured Color Coordinates*. Three (3) test specimens per candidate coating were subjected to a color analysis using a colorimeter. The test specimens were matched against the relevant color from FED-STD-595. A reading was taken on three different places on the sample. Standard acceptance criteria for this evaluation are as follows:

Test Methodology

Parameters	Color analysis using a colorimeter
Number of Panels[2]	Three (3) of each stack-up utilized in test.
Trials Per Panel	Three (3)
Target Criteria	No more than 1.0 ΔE using CIE LAB method from the relevant FED-STD-595 color.

Unique Equipment and Instrumentation

Colorimeter

Deviation from Test Methodology

None

5.2.3.1.2 Gloss

Test Description

This test covers the measurement of the specular gloss of nonmetallic specimens for glossmeter geometries of 60° and 85° in accordance with ASTM D 523, *Standard Test Method for Specular Gloss*. A glossmeter capable of reading at 60° and 85° was calibrated using a National Institute

[2] Test is non-destructive; panels may be reused for other tests.

of Standards and Technology (NIST) traceable standard. The instrument was then placed on the sample. A reading was taken on three different places on the sample. Standard acceptance criteria for this evaluation are as follows:

Test Methodology

	Gloss	**Flat**
Parameters	Gloss reading using gloss meter at 60° and 85°	
Number of Panels[3]	Three (3) of each stack-up utilized in test.	
Trials Per Panel	Three (3)	Three (3)
Target Criteria	Gloss: ≥ 90 at 60° Flat: ≤ 5 at 60° and ≤ 9 at 85°	

Unique Equipment and Instrumentation
Glossmeter capable of 60° and 85°

Deviation from Test Methodology
None

5.2.3.1.3 Dry Film Thickness

Test Description
Dry film thickness analysis was performed using eddy current. The test was conducted in accordance with ASTM D 7091, *Standard Practice for Nondestructive Measurement of Dry Film Thickness of Nonmagnetic Coatings Applied to Ferrous Metals and Nonmagnetic, Nonconductive Coatings Applied to Non-Ferrous Metals*. Three or more thickness readings, per ASTM D 7091, Section 8.3, were taken along the length of each test panel with the average dry film thickness reported.

Test Methodology

Parameters	Three or more thickness readings taken along length of each test panel with eddy current gauge
Number of Panels[4]	All panels
Trials Per Panel	Three (3)
Target Criteria	The formulation team recommended optimum coating thickness or a coating within the ranges specified in Table 9.

[3] Test is non-destructive; panels may be reused for other tests.
[4] Test is non-destructive; panels may be reused for other tests.

Unique Equipment and Instrumentation
Eddy current gauge

Deviation from Test Methodology
None

5.2.3.2 Adhesion Tests

5.2.3.2.1 Wet Tape Adhesion

Test Description
This test method covers a procedure for establishing acceptability of intercoat and surface adhesion of an organic coating by immersing the coating in water and applying pressure sensitive tape over a scribed area of the coating in accordance with ASTM D 3359, Method A, *Standard Test Method for Measuring Adhesion by Tape Test*. A coated specimen is soaked in distilled water for 24 hours. Two parallel lines one inch apart are then scribed on the test panel. An "x" is then scribed across the two parallel lines so that the smaller angle of the "x" is about 35° to 45°. All scribing shall be done with a diamond tip scriber or equivalent. The coating shall be scribed all the way to the substrate. A piece of 3M 250 tape (or equivalent) is placed over the incision and smoothed out. The tape is then removed rapidly at a 180° angle. The scribe area is inspected for peel away.

Test Methodology

Parameters	24 hours distilled water
Number of Panels	Three (3) of each stack-up utilized in test.
Trials Per Panel	One (1)
Target Criteria	No peel away; target rating of 4A or 5A

Unique Equipment and Instrumentation
- 1" masking tape code 3M 250 (or equivalent)
- 4.5 lb. roller

Deviation from Test Methodology
None

5.2.3.2.2 Cross Hatch Adhesion

Test Description
This test method covers a procedure for establishing acceptability of intercoat and surface adhesion of an organic coating applying pressure sensitive tape over a scribed area of the coating in accordance with ASTM D 3359, Method B, *Standard Test Method for Measuring Adhesion by Tape Test*. A lattice pattern of either six or eleven cuts, depending on coating thickness, in each direction is made in the coating. All scribing shall be done with a cross-hatch scriber. The coating shall be scribed all the way to the substrate. A piece of 3M 250 tape (or equivalent) is

placed over the incision and smoothed out. The tape is then removed rapidly at a 180° angle. The scribe area is inspected for peel away.

<u>Test Methodology</u>

Parameters	Number of cuts depending on dry film thickness • Thickness up to and including 2 mils, 11 cuts in both directions; spaced 1 millimeter (mm) apart • Thickness of 2-5 mils, 6 cuts in both directions; spaced 2 mm apart
Number of Panels	Three (3) of each stack-up utilized in test.
Trials Per Panel	One (1)
Target Criteria	No peel away; target rating of 4B or 5B

<u>Unique Equipment and Instrumentation</u>

- Cross hatch scriber
- 1” masking tape conforming to 3M 250 (or equivalent)
- 4.5 lb. roller

<u>Deviation from Test Methodology</u>
None

5.2.3.2.3 MEK Rub

<u>Test Description</u>
One panel for each coating was tested after cure using the solvent resistance test specified in MIL-PRF-85285D (paragraph 3.8.5). The requirement was to withstand 25 double rubs (50 passes) with a cotton terrycloth rag soaked with methyl ethyl ketone (MEK) solvent using firm finger pressure. Exposure of the primer indicated improper cure.

<u>Test Methodology</u>

Parameters	25 double rubs
Number of Panels	Three (3) of each stack-up utilized in test.
Trials Per Panel	One (1)
Target Criteria	No exposure of primer.

<u>Unique Equipment and Instrumentation</u>

- None

<u>Deviation from Test Methodology</u>

None

5.2.3.2.4 Stencil Coat Adhesion

Test Description
The test determined the ability of UV-curable coatings to adhere to standard MIL-PRF-85285 topcoat or to an APC-qualified MIL-PRF-85285 topcoat when utilized as a stencil coating. Six panels of the stack-up 36173 Flat Gray Minimum Performance Control and six panels of the stack-up 36173 Flat Gray Optimum Performance Control were utilized for each UV-curable coating being tested. The most common method of surface preparation for stencil coating is light sanding, which was used for this test.

Test Methodology

Parameters	See text
Number of Panels	Six (6) each of: • 36173 Flat Gray Minimum Performance Control (per UV-cure coating tested) • 36173 Flat Gray Optimum Performance Control (per UV-cure coating tested)
Trials Per Panel	One (1) per panel
Target Criteria	No peel away; target rating of 4A or 5A

Unique Equipment and Instrumentation
- See Section 5.2.3.2.1 and 5.2.3.2.2

Each panel was lightly sanded with 320 grit sandpaper. After sanding, the panels were wiped with a rag wet with suitable solvent to remove dust and debris. The UV-curable coating being tested was then sprayed and applied to the activated topcoat surface of each panel and then cured as per established UV cure procedure. The panels were then tested for adhesion.

Deviation from Test Methodology
For JTP testing conducted on the CTC/BBM developed coating samples, one 36173 Flat Gray Minimum Performance Control and one 36118 Flat Gray Minimum Performance Control were utilized due to material limitations. However, these panels were 12 inch by 12 inch and multiple adhesion trials conducted on the surface of each panel. In addition, state-of cure was determined by pencil hardness and MEK rub rather than adhesion testing.

5.2.3.2.5 UV-Curable Coating Cure Conditions

Test Description
To validate cure capability in less than favorable conditions, for each UV-curable topcoat one set of three (3) panels were cured at the following environmental conditions:

- 77° ± 5° Fahrenheit (ºF) / 50 ± 5% Relative Humidity (RH) (**control temperature**)
- 90° ± 5 ºF / 80% ± 5% RH (**hot/wet**)
- 90° ± 5 ºF / 20% ± 5% RH (**hot/dry**)
- 60°± 5 ºF / 80% ± 5% RH (**cold/wet**)
- 60° ± 5 ºF / 20% ± 5% RH (**cold/dry**)

Each panel was subjected to wet tape and cross hatch adhesion testing.

<u>Deviation from Test Methodology</u>
For JTP testing conducted on coating samples developed by the CTC/BBM, this coating cure condition testing was not conducted. Testing was excluded due to lack of an available environmental chamber large enough for coating cure.

5.2.3.3 Flexibility Tests

5.2.3.3.1 Low Temperature Mandrel Bend

<u>Test Description</u>
Low temperature flexibility is determined by use of a mandrel in accordance with ASTM D 522, *Standard Test Methods for Mandrel Bend Test of Attached Organic Coatings*. A coated panel is placed in a test chamber at the specified temperature and length of time. The mandrel is placed in the chamber with the test panels. Upon completion of the specified exposure time the test panel is immediately bent over the mandrel (coating side of test panel is up; non-coated side is against the mandrel). Bending of the test panel over the mandrel should be completed within the test chamber to prevent change in panel and mandrel temperature. The panel is then inspected for cracking and adhesion loss.

<u>Test Methodology</u>

	Low Temperature
Parameters	At -51 ± 3°C (-60 ± 5°F), for 12 – 26 hours. High and semi-gloss use 1”mandrel; Flat use 2”mandrel.
Number of Panels	Three (3) of each stack-up utilized in test.
Trials Per Panel	One (1)
Target Criteria	No cracking or adhesion loss

.

<u>Unique Equipment and Instrumentation</u>
1 inch and/or 2 inch mandrel.

<u>Deviation from Test Methodology</u>
None

5.2.3.3.2 GE Impact

Test Description

Per ASTM D 6905, *Standard Test Method for Impact Flexibility of Organic Coating*, the GE Impact analysis procedure is used for determining the ability of a coating film and its substrate to resist shattering, cracking, or chipping when the film and the substrate are distended beyond their original form by impact. A coated panel is placed coated side down in the testing apparatus. A GE impact indenter is dropped from a measured height such that the full impression of the indenter is obtained. The full impression of the indenter must be made in the panel in order for the test to be valid. The panel is then inspected with 10-power magnification for cracks, crazing or loss of adhesion where the impact occurred. Topcoat, candidate coatings should exhibit no cracking, crazing, loss of adhesion, or other coating damage at 40% elongation.

Test Methodology

Parameters	21 ± 5°C (70 ± 10°F)
Number of Panels	Three (3) of each stack-up utilized in test.
Trials Per Panel	One (1)
Minimum Target Criteria	40% elongation for aircraft use and 5% elongation for Ground Support Equipment; no cracking, crazing, or loss of adhesion.
Optimum Target Criteria	Minimum 60% elongation for gloss and semi-gloss and 40% for flat

Unique Equipment and Instrumentation

IM-172-GE Impact Tester

Deviation from Test Methodology

None

5.2.3.4 Resistance Tests

5.2.3.4.1 Pencil Hardness

Test Description

Pencil Hardness is used to determine the hardness of an organic coating on a substrate. Testing will be conducted in accordance with ASTM D 3363, *Standard Test Methods for Film Hardness by Pencil Test*. A coated test panel is placed on a firm horizontal surface. The pencil is held firmly against the film at a 45° angle (point away from the operator) and pushed away from the operator in a 6.5 mm (1/4 inch) stroke. Testing starts with the hardest pencil and continues down the scale of hardness until the pencil that will not scratch the film is identified.

Test Methodology

Parameters	*Scratch Hardness* – The hardest pencil that will not rupture or scratch the candidate coating
Number of Panels	Three (3) of each stack-up utilized in test.
Trials Per Panel	Two (2)
Target Criteria	B or harder; not to be used as pass/fail criteria but to establish initial hardness data point for fluid resistance evaluation

Unique Equipment and Instrumentation
None

Deviation from Test Methodology
None

5.2.3.4.2 Fluid Resistance – Lubricating Oil, Hydraulic Fluid, JP-8, Skydrol, Deionized Water

Test Description
This test method covers the determination of the effects of six fluids on organic finishes resulting in any objectionable alteration in the surface such as discoloration, change in gloss, blistering, softening, swelling, loss of adhesion, or other special conditions. The minimum requirements were exposure to lubricating oil conforming to MIL-PRF-23699, 24 hour exposure to hydraulic fluid conforming to MIL-PRF-83282, and 7 day exposure to JP-8 fuel. The optimal requirements were for exposure to lubricating oil conforming to MIL-PRF-7808, 7 day exposure to hydraulic fluid conforming to MIL-PRF-83282, 30 days exposure to JP-8, exposure to deionized water, and exposure to Skydrol LD-4.

Expose a separate set of three test panels to each of the following fluids at the designated conditions:

a. MIL-PRF-23699 (specifically Mobil Jet 254) and MIL-PRF-7808 – Prepare one set of three test panels for each lubricant. Prior to exposure, measure the color of three panels, and then completely immerse them for 24 hours @ 250±5 ºF (121±3 ºC).

   Note: MIL-PRF-7808 was tested at the request of OO-ALC. Mobil Jet 254 was used as the specific MIL-PRF-23699 qualified oil at the request of the United States Coast Guard, Elizabeth City Aviation Logistics Center.

b. MIL-PRF-83282 – Prepare two sets of three test panels each. Prior to exposure, measure the color of panels. To test for target criteria, completely immerse one set of three test panels for 24 hours @ 150±5 ºF (65.6±3 ºC). To test for optimum target criteria, completely immerse one set of three test panels for seven (7) days @ 150±5 ºF (65.6±3 ºC).

c. Jet Fuel JP-8 +100 – Prepare two sets of three test panels each. Prior to exposure, measure the color of panels. To test for target criteria, completely immerse one set of three test panels for Seven (7) days @ 77±5 ºF (25±3 ºC). To test for optimum target criteria, completely immerse one set of three test panels for 30 days @ 77±5 ºF (25±3 ºC).

d. Deionized Water (ASTM D 1193 Type IV) – Prior to exposure, measure the color of three panels in, and then completely immerse them for 30 days @ 120±5 ºF (49±3 ºC)

e. Skydrol LD-4 – Prior to exposure, measure the color of three panels, then scribe three additional panels with a 4± 0.125 inch diagonal line, and then place the six panels in a horizontal position coating side up in a test area maintained at 77± 5 ºF (25±3 ºC). Using Skydrol LD-4 at 77±5 ºF (25±3 ºC), wet the six panels once each day (no immersion) for 30 days.

After each exposure, remove the panels, and immediately evaluate for blistering and film delamination. After evaluation, gently clean the MIL-PRF-23699, MIL-PRF-83282, Jet Fuel, and the unscribed Skydrol LD-4 panels with the coating system cleaner, and rinse thoroughly with water. Blot the panels dry and allow to air dry for 1-hour, and then measure the final color. After the color measurement has been made, test for the final adhesion and hardness. Compare the average of the initial values with the average of the final values to assess compliance.

Test Methodology

Parameters	Lubricating oil (24 hours immersion) maintained at 250 ± 5 °F (121 ± 3 °C); hydraulic fluid (24 hours target, seven (7) days optimum immersion) maintained at 66 ± 3 °C (150 ± 5 °F); JP-8 (seven (7) days target, 30 days optimum immersion) maintained at 25 ± 3 °C (77 ± 5 °F); deionized water (30 days immersion) maintained at 25 ± 3 °C (77 ± 5 °F); Skydrol (wet once each day for 30 days; no immersion) maintained at 25 ± 3 °C (77 ± 5 °F)
Number of Panels	Twenty-seven (27) of each coating stack-up tested.
Trials Per Panel	One (1) (of each test)
Target Criteria	Softening of no more than two (2) pencil hardness units or color change (ΔE) of $\leq$ three (3) for: lubricating oil (24 hours immersion), hydraulic fluid (24 hours immersion), or JP-8 (seven {7} days immersion)
Optimum Target Criteria	Softening of no more than two (2) pencil hardness units, no peel away from scribe for Skydrol panels, and color change (ΔE) of $\leq$3 for: lubricating oil (24 hours immersion), hydraulic fluid (seven {7} days immersion), or JP-8 (30 days immersion); Skydrol (wet each day 30 days), and deionized water (30 days immersion)

Unique Equipment and Instrumentation
Fluids as noted.

Deviation from Test Methodology
For JTP testing conducted on coating samples developed by the CTC/BBM, only the three minimum target criteria tests were conducted.

5.2.3.4.3 Accelerated Weathering

Test Description
This test method covers the ability of a coated sample to withstand accelerated weathering in a weatherometer chamber when tested in accordance with ASTM G 155, *Standard Practice for Operating Xenon Arc Light Apparatus for Exposure of Non-Metallic Materials*. Three performance samples of each type were exposed for a minimum performance criteria test of 500 hours and an optimal performance criteria test of 3,000 hours, with color and gloss differences checked every 500 hours.

As an optimal criteria test, at the conclusion of 500 hours the Low Temperature Flexibility and GE Impact Flexibility of the coatings were tested for three flexibility panels of each type. At the conclusion of 3,000 hours, the Low Temperature Flexibility and GE Impact Flexibility of the coatings were tested for three flexibility panels of each type.

Test Methodology

Parameters	0.35 – 0.5 Watts/m^2 a wavelength of 340 nm; Incident for 500 hours (minimum) to 3,000 hours (maximum)
Type / Number of Panels	Three (3) each color/gloss panels of each coating stack-up tested. Twelve (12) flexibility panels of each coating stack-up tested (optimal requirements testing only).
Trials Per Panel	Three (3) of each color/gloss test. One (1) of each flexibility test
Minimum Target Criteria	Performance (2024-T3) panels: Color change (ΔE) of less than 1; Minimum gloss readings of 80 for “gloss”; max. 5 for “flat” after 500 hours
Optimum Target Criteria	Performance (2024-T3): Color change (ΔE) of less than 1; Minimum gloss readings of 90 for “gloss”; maximum five (5) for “flat” after 3000 hours Flexibility (2024-O) panels: Low Temperature Flexibility: No cracking or adhesion loss over 1-inch bend for gloss and semi-gloss or 2-inch bend for flat coatings after 500 hours Flexibility (2024-O): GE Impact Flexibility: 40% elongation for gloss or 20% for flat colors; no cracking, crazing, or loss of adhesion after 500 hours. Flexibility (2024-O) panels: Low Temperature Flexibility: No cracking or adhesion loss over 1 inch bend for gloss or 2 inch bend for flat coatings after 3000 hours Flexibility (2024-O) panels: GE Impact Flexibility: 40% elongation for gloss or 20% for flat colors; no cracking, crazing, or

	loss of adhesion after 3000 hours.

Unique Equipment and Instrumentation
Xenon Arc Weatherometer

Deviation from Test Methodology
For JTP testing conducted on coating samples developed by CTC/BBM, only the three minimum target criteria tests were conducted.

5.2.3.4.4 Heat Resistance

Test Description
This test method determines the ability of coatings to resist exposure to high temperatures without color change, loss of adhesion or loss of flexibility. Minimum target criteria requires coated panel be exposed to 121 ± 3 °C (250 ± 5 °F) for no less than 60 minutes in accordance with FED STD 141, method 6051. After exposure, the panel will be tested for color change as per the methodology specified in 4.1.1. Optimum target criteria requires the coated panel be exposed to 176.5 ± 3 °C (350 ± 5 °F) for no less than 4 hours in accordance with FED STD 141, method 6051. After exposure, the panel will be tested for color change, adhesion and low temperature flexibility.

Test Methodology

Parameters	Exposure to 250 ± 5 °F (121 ± 3 °C) for no less than 60 minutes in accordance with FED STD 141, method 6051.
Number of Panels	Three (3) of each coating stack-up tested for minimum target criteria. Six (6) of each coating stack-up tested (including three flexibility test panels) for optimum target criteria.
Trials Per Panel	One (1)
Minimum Target Criteria	ΔE of less than 1 after exposure to 250 ± 5 °F (121 ± 3 °C) for no less than 60 minutes
Optimum Target Criteria	Color Change: ΔE of less than 1 after exposure to 350 ± 5 °F (176.5 ± 3 °C) for no less than 4 hours. Cross Hatch Adhesion: rating of 4A or higher Flexibility: No cracking or adhesion loss over 1 inch bend for gloss and semi-gloss or 2 inch bend for flat coatings

Unique Equipment and Instrumentation
Oven capable of reaching 350° F (180 °C)

Deviation from Test Methodology

For JTP testing conducted on coating samples developed by CTC/BBM, only the minimum target criteria tests were conducted.

5.2.3.4.5 Humidity Resistance

<u>Test Description</u>
This test method covers the ability of a coated sample to withstand exposure to high humidity when tested in accordance with ASTM D 2247, *Standard Practice for Testing Water Resistance of Coatings in 100 % Relative Humidity*. The samples are exposed for 30 days in a humidity cabinet maintained at 120 ± 3 °F (49 ± 2 °C) and 100% RH. After exposure the samples are evaluated for blistering, softening, loss of adhesion or other coating defects

<u>Test Methodology</u>

Parameters	Exposure for 30 days in a humidity cabinet maintained at 120 ± 3 °F (49 ± 2 °C) and 100% relative humidity (RH)
Number of Panels	Three (3) of each coating stack-up tested.
Trials Per Panel	One (1)
Target Criteria	No blistering, softening, loss of adhesion or other coating defects

<u>Deviation from Test Methodology</u>
None.

<u>Unique Equipment and Instrumentation</u>
Humidity cabinet.

5.2.3.4.6 Cleanability

<u>Test Description</u>
This test method determines the ability of coatings to maintain a cleaning efficiency of not less than 75%. The three test panels must be first soiled then cleaned, according to the following procedure. Note that this test is applicable only to non-black panels. Black color coatings were not tested. Test steps are as follows.

A. Preparation of artificial soil
50.0 ±0.5g of carbon black and 500.0 ±1.0g of hydraulic fluid (MIL-PRF-83282) are placed in a container. The soil is homogenized using a high shear mixer for 15 ±1 minutes, followed by stirring or shaking the mixture by hand.

B. Preparation of test panels
Using a clean, hog bristle brush, the coating of each test panel is lightly scrubbed with a 1.0% (by weight) solution of Alconox detergent, or equivalent, in reagent water. Each panel is rinsed thoroughly three times with reagent water and dried for no less than18 hours at 120 ±4 °F (49 ±2

°C). Using the methodology outlined in section 4.1.1, the color value of the clean panel is verified and designated value "A."

C. Soiling of test panels
Using a soft-bristle brush, the painted surfaces of the test panels are coated with the prepared soil. Excess soil is removed by covering the test panel surface with folded absorbent tissue and exerting pressure by rolling the tissue with a five (5) pound rubber roller. This blotting procedure is repeated twice. The soiled surface is brushed parallel to the long dimension of the test panels, using ten (10) brush strokes in each direction. The test panels are baked at 220 ±4 °F (105 ±2 °C) for 60 ±1 minutes. Determine the L value of the coating in accordance with ASTM D2244. Using the methodology outlined in section 4.1.1, the color value of the cleaned panels is verified and designated value "B."

D. Cleaning
Within 4 hours of soiling the test panels, the cleanability test as specified in MIL-PRF-85570, is conducted using the type II control formulation. The Type II cleaning formulation is prepared by diluting one (1) part cleaner on the MIL-PRF-85570 Qualified Products List (QPL) with 14 parts water and then scrubbed with a brush until visual evaluation suggests the artificial soil is no longer being removed. Using the methodology outlined in section 4.1.1, the color value of the cleaned panels is verified and designated value "C."

E. Calculation
The cleaning efficiency achieved on each test panel is calculated as follows:
Cleaning efficiency (%) = [(C - B) ÷ (A - B)] x 100

Test Methodology

Parameters	See text.
Type / Number of Panels	Three of each coating stack-up tested.
Trials Per Panel	One (1)
Acceptance Criteria	Cleaning efficiency of 75% or greater.

Deviation from Test Methodology
None.

Unique Equipment and Instrumentation
None.

5.2.3.4.7 Salt Spray Test

Test Description
This method covers the establishment of the required conditions of the salt spray test in which test specimens are placed in a controlled corrosive heated environment for a specified length of time in accordance with ASTM B-117, *Standard Practice for Operating Salt Fog Apparatus*. A

coated panel is scribed with an “x” using a diamond tip scriber or equivalent in order to achieve a scribe 20 to 40 mils wide and 4 to 6 mils deep into the surface of the substrate. The back and edges of the panel are covered with wax, paint, tape, or any other material that will prevent corrosion products from contaminating the chamber. The panels are placed in the salt spray chamber at a 15° to 30° angle from the vertical. The salt solution is verified to be 5% +/- 1% and pH is verified to be 6.5 to 7.2 at 35° C. The chamber is closed and the specimens are evaluated for surface corrosion and creepage from scribe every 500 hrs.

This test is normally only performed on primers and was requested by USN stakeholders. For this reason, it was considered an optimum performance criteria test.

Test Methodology

Parameters	5% salt solution/2,000 hours
Number of Panels	Three (3) of each coating stack-up tested.
Trials Per Panels	One (1)
Target Criteria	No blisters or undercutting from the scribe; no discoloration in the scribe and no pitting in the scribe

Deviation from Test Methodology
As an optimum performance criteria test, salt spray corrosion testing was not performed on coating samples developed by the CTC/BBM.

Unique Equipment and Instrumentation
Salt fog cabinet

5.2.3.5 Repairability

Test Description
This test is not required under any mil-spec, but was conducted as an optimum performance criteria test in anticipation of supporting a successful transition.

The method determines the ability of UV-curable coatings to adhere to itself, to standard MIL-PRF-85285 topcoat, or to an APC-qualified MIL-PRF-85285 topcoat during standard repair scenarios. Panels of size 12” by 12” by .032” were utilized in this test. For each candidate UV-curable coating, the following five scenarios were tested:

1) UV-curable used to repair weathered MIL-PRF-85285 topcoat

A 12” x 12” panel of 36173 Flat Gray Minimum Performance Control stack-up is subjected to accelerated weathering for 500 hours. The panel is scuff-sanded to activate the topcoat. The coating is divided up into two halves. On one half, the UV-curable candidate coating is applied. On the other half, a light spray of the MIL-PRF-23377 primer is applied and allowed to cure a minimum of four (4) hours, and the side is then coated and cured with the UV-curable candidate coating. A wet tape adhesion and cross hatch adhesion test are conducted on each side of the coating. Figure 12 lays out the coating and test pattern.

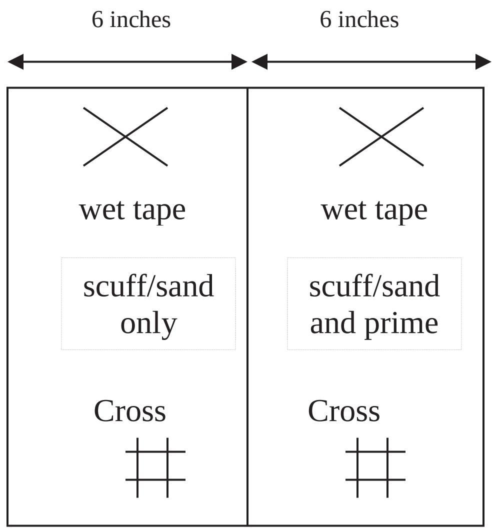


Figure 12. Coating and Test Diagram

2) UV-curable used to repair weathered APC-qualified MIL-PRF-85285 system

A 12” x 12” panel of 36173 Flat Gray Optimum Performance Control stack-up is subjected to accelerated weathering for 500 hours. The panel is scuff-sanded to activate the topcoat. The coating is divided up into two halves. On one half, the UV-curable candidate coating is applied. On the other half, a light spray of the MIL-PRF-23377 primer is applied and allowed to cure a minimum of four (4) hours, and the side is then coated and cured with the UV-curable candidate coating. A wet tape adhesion and cross hatch adhesion test are conducted on each side of the coating.

3) UV-curable used to repair weathered UV-cure coating system

A 12” x 12” panel of UV-Cure Performance Specimen stack-up is subjected to accelerated weathering for 500 hours. The panel is scuff-sanded to activate the topcoat. The coating is divided up into two halves. On one half, the UV-curable candidate coating is applied. On the other half, a light spray of the MIL-PRF-23377 primer is applied and allowed to cure a minimum of four (4) hours, and the side is then coated and cured with the UV-curable candidate coating. A wet tape adhesion and cross hatch adhesion test are conducted on each side of the coating.

4) MIL-PRF-85285 topcoat used to repair weathered UV-cure coating system

A 12” x 12” panel of UV-Cure Performance Specimen stack-up is subjected to accelerated weathering for 500 hours. The panel is scuff-sanded to activate the topcoat. The coating is divided up into two halves. On one half, the 36173 Flat Gray MIL-PRF-85285 topcoat is applied. On the other half, a light spray of the MIL-PRF-23377 primer is applied and allowed to cure a minimum of four (4) hours, and the side is then coated and cured with the 36173 Flat Gray MIL-PRF-85285 topcoat. A wet tape adhesion and cross hatch adhesion test are conducted on each side of the coating.

5) APC MIL-PRF-85285 topcoat used to repair weathered UV-cure coating system

A 12” x 12” panel of UV-Cure Performance Specimen stack-up is subjected to accelerated weathering for 500 hours. The panel is scuff-sanded to activate the topcoat. The coating is divided up into two halves. On one half, the 36173 Flat Gray APC-qualified MIL-PRF-85285 topcoat is applied. On the other half, a light spray of the MIL-PRF-23377 primer is applied and allowed to cure a minimum of four (4) hours, and the side is then coated and cured with the 36173 Flat Gray APC-qualified MIL-PRF-85285 topcoat. A wet tape adhesion and cross hatch adhesion test are then being conducted on each side of the coating.

Test Methodology

Parameters	See text
Number of Panels	Per candidate UV-curable coating tested, one (1) 12” x 12” panel each of: • 36173 Flat Gray Minimum Performance Control • 36173 Flat Gray Optimum Performance Control Per candidate UV-curable coating tested, three (3) 12” x 12” panels each of: • UV-cure Coating Performance Specimen
Trials Per Panels	One (1)
Target Criteria	No peel away; target rating of 4A or 5A

Repair of the Panel
Apply the repair coating to achieve a 3-5 mil dry film thickness of reapplied coating.

Deviation from Test Methodology
As an optimum performance criteria test, repairability testing was not performed on coating samples developed by the CTC/BBM.

Unique Equipment and Instrumentation
None

5.2.3.6 Stripability

Stripability testing is not required under any mil-spec, but was conducted as an optimum performance criteria test in anticipation of supporting a successful transition.

5.2.3.6.1 Chemical Removers

Test Description
This test method covers a procedure for establishing acceptability of chemical paint removers to remove the UV-cured and standard coating system. One type of stripper used was identified by OO-ALC. Elizabeth City Aviation Logistics Center identified a second stripper, RemovAll™ Epoxy and Polyurethane Paint Remover manufactured by Napier Environmental Technologies.

Test Methodology

Parameters	Processed in accordance with CLG-LP-043-Rev 00
Number of Panels	Three for each coating stack-up tested.
Trials Per Panel	One (1)
Target Criteria	Complete removal of coating

Unique Equipment and Instrumentation

- Test panel support rack designed to hold the test panels at a 60° ± 5° angle.
- Paraffin wax or aluminum tape to seal edges of test panels
- Stiff bristled brush for scrubbing panels after stripper exposure.
- 1000-milliter glass beakers (or other glass containers for securing panels in the oven)
- Glass rods to separate panels within the beakers during oven exposure.

5.2.3.6.2 Blast Media Removers

Test Description
This test method covers a procedure for establishing acceptability of dry media blasting to remove the UV-cured and standard coating system. Nozzle pressure will be 50 pounds per square inch (psi) or below using a 0.5-inch inside diameter nozzle, a venturi type nozzle is preferable. The test panel is placed in a cabinet blaster; standoff distance is 8-12 inches with an angle of attack of 30°to 60°. The time required to remove the coating to the substrate is recorded.

Test Methodology

Parameters	0.05 blast nozzle, < 50 PSI, 30° to 60° blast angle
Number of Panels	Three for each coating stack-up tested.
Trials Per Panel	One (1)
Target Criteria	Complete removal of coating; no visible damage to substrate

Unique Equipment and Instrumentation
- Blast cabinet with 0.5-inch hose and 0.5-inch blast nozzle

5.2.3.6.3 Laser Coating Removal System

Test Description

This test method covers a procedure for establishing acceptability of a laser system to remove the UV-cured and standard coating system. Panels were stripped using a prototype 6000W fiber laser system for aircraft laser coating removal system in Johnstown, Pennsylvania. The time required to remove the coating to the substrate was recorded.

Test Methodology

Parameters	6000W fiber laser system
Number of Panels	Three for each coating stack-up tested.
Trials Per Panel	One (1)
Target Criteria	Complete removal of coating; no visible damage to substrate

Unique Equipment and Instrumentation

- Laser coating removal system

5.3 Field Testing

No field testing was carried out under this effort. Two attempts were made to carry out application trials at OO-ALC. In both attempts, a successful cure was not achieved on-site and no detailed observations could be collected. Section 6 will describe the results of these attempted application trials.

6.0 PERFORMANCE ASSESSMENT

6.1 DSM Desotech Gloss White Performance Results

It was known from the screening testing described in Section 2.2.1 that the available gloss white coatings were not as far advanced towards meeting DoD aerospace requirements as the flat black and that this was the riskier of the two development efforts. Of the two gloss white coatings submitted, the DSM Desotech coating was judged to be superior due to its superior adhesion as compared to the Red Spot Coating, which was unable to demonstrate either wet tape or cross hatch adhesion. BMS might potentially have formulated gloss white as well as flat black and gray colors, but this option was not initially pursued for two reasons:

- The performance differences between the flat gray and gloss white coatings submitted by both DSM Desotech and Red Spot indicated that gloss white was a substantially different coating problem as compared to flat colors. No testing had been done on any effort by BMS to produce UVA cure gloss coatings.
- Asking BMS to formulate a gloss white would require splitting the efforts of BMS's internal development team between two different product types.

As of the end of the screening testing, the DSM Desotech coating failed to meet the following requirements:

- Gloss (did not meet initial 90 at 60 degrees requirement)
- Adhesion (marginal failure on cross hatch)
- Weathering (color change over delta 1; but gloss loss <10 at 500 hours)
- GE Impact Flexibility (no UV-curable coating met this requirement)
- Heat resistance (color change over 3 at 1 hr)
- Opacity (coating was translucent; primer partially visible)
- Fluid resistance (color change only; no adhesion loss for most fluids)

DSM was provided a copy of the JTP and MIL-PRF-85285 detailing exactly what requirements its coating would be expected to meet. DSM laboratory work began on February 17, 2009, and progress by DSM was tracked through semi-regular teleconferences and monthly reports. A month-by-month account of DSM's efforts is in Appendix C, DSM Desotech Month by Month Progress.

As of July 2009, DSM was still failing to achieve improvements in adhesion. In addition, DSM's initial weathering testing on their most promising coatings showed a catastrophic failure to retain gloss in weathering resistance testing.

A teleconference was held on August 10, 2009, with DSM Desotech to determine if a viable path forward existed to meet DoD aerospace coating requirements. Given the failure to make progress towards improving coating to meet performance properties, the gloss white effort with DSM Desotech was formally terminated on September 7, 2009.

6.2 BMS/Deft Flat Coating Performance Results

As discussed in Section 2.2.1, the BMS/Deft UV-curable black coating identified by the manufacturer as "Deft 21BK001" successfully achieved most aerospace requirements during screening testing conducted by the CTIO in early 2008. BMS was contracted to optimize this coating beginning in February 2009. Table 10 summarizes a detailed write-up given to BMS evaluating the performance of 21BK001 and discussing where improvements were required to meet USAF needs based on the requirements of the JTP.

Table 10. Improvements Requested to 21BK001

Property Tested	Deft 21BK001 (Black 370938)	Requirement given to BMS
FED-STD-595 chip for 37038 Black comparison	ΔE of 3.5 from color chip	Needs closer match, also looking for match to gray colors
Gloss at 60° & 85°	6.3 @ 60°; 38.4 @ 85°	Needs to be ≤5 @ 60°; ≤9 @ 85°
Adhesion /Pencil hardness	5A (wet tape); 5B (crosshatch); F hardness	Pass, coating performs well.
Low Temp & GE Impact Flexibility	Pass low temp; 2% GE Impact Flexibility	2% is too low; goal is 40%
Lube Oil Resistance	Hardness F drops to HB; Adhesion 5A/5B; 0.2 ΔE color change; no blistering	Pass, coating performs well.
Hydraulic Fluid Resistance (24 Hr.)	Hardness F drops to HB; Adhesion 5A/5B; no blistering	Pass, coating performs well.
Hydraulic Fluid Resistance (7 day)	Hardness stays at F; Adhesion 5A/5B; 0.1 ΔE color change; no blistering	Pass, coating performs well.
Jet Fuel Resistance (7 day)	Hardness F drops to HB; Adhesion 5A/5B; no blistering	Pass, coating performs well.
Jet Fuel Resistance (30 day)	Hardness F drops to HB; Adhesion 5A/5B; 0.1 ΔE color change; no blistering	Pass, coating performs well.
Skydrol Resistance (30 day)	Hardness F drops to HB; Adhesion 5A/5B; 0.6 ΔE color change; no blistering	Pass, coating performs well.
Deionized Water Resistance (30 day)	Hardness F drops to HB; Adhesion 5A/5B; 0.4 ΔE color change; no blistering	Pass, coating performs well.
Heat Resistance	ΔE Color 0.1 @ 1hr 250; 0.4 @ 4hr 350; Adhesion 5B	Pass, coating performs well.
500 hrs weathering	ΔE Color 0.2; gloss 3.6 @ 60°	Pass, coating performs well.
3000 hrs weathering	ΔE Color 0.3; gloss 2.1 @ 60°	Pass, coating performs well.

Table 11 summarizes a timeline of the internal development and testing of the BMS/Deft UV-curable flat black and gray coatings. Events within this table will be summarized in more detail in the following sections.

Table 11. Timeline of BMS/Deft UV-Curable Flat Coating

Timeline	Milestones	UVA Cure Coating	Basis of Testing	Outcome
Dec 2007	BMS/Deft Conduct Initial Field Demo at Iowa Air National Guard	Black 37038 (stencil) Gray 36118 (stencil)	Visual	Gray failed to cure
Jan – Jul 2008	CTIO Round 2 testing of COTS Coatings	Deft 21BK001 (Black 37038 stencil) – same as above	Tests standards based on MIL-PRF-85285	Gloss, flexibility, and color are not meeting requirements
Mar 2008 – Jun 2008	ESTCP Awarded, and Funded			
Jun – Sep 2008	Joint Test Plan written and approved		JTP based on spec requirements, stakeholder requests, and comparison to controls	
Oct 08 – Jan 09	RFP to BMS to get Topcoat to meet JTP requirements	Deft 21BK001 (baseline); Target 37038 black, 36118 gray, and 36173 gray	Laboratory test standards described in JTP	
Feb 09 – Jun 09	BMS/Deft Reformulation efforts	Various versions of blacks and grays	BMS internal testing against JTP requirements	Gloss reduction and flexibility increase severely impacted weathering resistance properties. Conclusion: New base resin needed to be formulated and further development to address color and gloss.

Table 11 Timeline of BMS/Deft UV-Curable Flat Coating (Continued)

Timeline	Milestones	UVA Cure Coating	Basis of Testing	Outcome
Jul 2009 – Aug 2009	BMS/Deft Base Resin Reformulation	Various resins used for black coating	BMS internal development testing against JTP requirements and control coatings	New resins showed progress in balancing low gloss, flexibility, and weather resistance requirements. Chalking problem in weathering discovered and addressed.
Sep 2009		BMS final formulation passed to Deft.		BMS passed coating to Deft for color matching and final refinement; BMS stated coating could meet JTP properties except being slightly above spec for gloss at 85° (per stakeholders a minor issue)
Oct 2009 – Nov 2009	Deft Color Matching	21BK003 (37038) - Black 21GY001 (36173) - Gray 21BY002 (36118) - Gray	MIL-PRF-85285	Deft color matched and did adhesion, resistance, and 500 hr weathering testing on formulation. Topcoats reported to pass except one fail on flexibility.
Dec 2009	Topcoats shipped to Battelle and sprayed for JTP testing	21BK003 (37038) Black sprayed 21GY001 (36173) Gray sprayed 21BY002 (36118) Gray unusable due to pigment float; new batch requested	To be tested against JTP	Sag issues; coatings could not be sprayed vertically;
Feb 2010	Anti-sag added and pigment float issue fixed by Deft. Re-sprayed by Battelle.	21BY002 (36118) Gray – new batch with anti-sag and new dispersant		Anti-sag properties became something the team evaluated from this point forward

Table 11 Timeline of BMS/Deft UV-Curable Flat Coating (Continued)

Timeline	Milestones	UVA Cure Coating	Basis of Testing	Outcome
Jan 2010 – May 2010	Battelle JTP testing	21BK003 (37038) - Black 21GY001 (36173) - Gray 21BY002 (36118) – Gray new batch with anti-sag	JTP	Failures in adhesion, flexibility, fluid resistance, and other properties. Inconsistent with Deft-reported internal testing.
Apr 2010 – Jun 2010	BMS/Deft created new coating batches for planned demonstration	21BK003 (37038) – Black new batch with pigment dispersant and anti-sag agent 21GY001 (36173) - Gray new batch with pigment dispersant and anti-sag agent 21BY002 (36118) – Gray new batch		Initial discussion of Battelle results. Deft suggested application error to explain poor Battelle performance, stated full confidence in ability of coatings to proceed to Dem/Val.
Jul 2010	Demo at Hill AFB; BMS, Deft, and lamp manufacturer present	With pigment dispersant and anti-sag: 21BK003 (37038) - Black 21GY001 (36173) - Gray 21BY002 (36118) - Gray	Apply to a primer to simulate "real world" Hardness Adhesion	No cure was achieved for any of the coatings
Aug 2010 – Sep 2010	Failure Analysis and Determine Path Forward	With pigment dispersant and anti-sag: 21BK003 (37038) - Black 21GY001 (36173) - Gray 21BY002 (36118) - Gray	Adhesion and hardness testing used as "state of cure" testing	Deft provided data showing a degrading dispersant was responsible for poor coating cure; began reformulating new batches
Oct 2010 – Nov 2010	Screening testing of new coating batches	With new pigment dispersant and anti-sag: 21BK003 (37038) - Black 21GY001 (36173) - Gray 21BY002 (36118) - Gray	Adhesion and hardness testing used as "state of cure" testing	Screening testing at CTC showed that the gray coatings suffered slight to severe adhesion failure
Dec 2010	Compare CTC results to Deft results	New batch with NEW pigment dispersant and anti-sag:	Determine cause of screening testing failures	Performance by gray coatings was too inconsistent for stakeholder confidence;

				coating effort terminated.

6.2.1 BMS/Deft Initial Flat Coating Internal Development and Testing Effort

Task kick-off was held on January 29, 2009, with an initial anticipated timeline of five months. Based on the proposed schedule, the coatings were expected to be delivered to CTC for JTP testing by the end of July 2009. During the kick-off meeting, personnel from BMS visited the CTIO to view the panels from the CTIO's testing and the lamp equipment with which coating cure would be evaluated. Following this meeting, CTC maintained regular communications with BMS during flat topcoat development effort through regular reports and teleconferences. Some of the more significant updates are discussed here.

<u>February/March Status</u>
During this initial technical effort, the focus was on reducing gloss in the original 21BK001 stencil coating. Most other properties were considered to have been already met, with increasing flexibility the next target after meeting gloss requirements.

<u>April Status</u>
BMS determined that flexibility would be a difficult requirement using the baseline 21BK001 resin and that it would be necessary to investigate new base resins for improved flexibility. There was concern that 40% flexibility might not be achieved. Initial results of the new resins were noted as exceeding 20% GE Impact flexibility, which was regarded as very positive results. Additionally, BMS created some gray versions of the formulation for comparison of properties. Coating was reported as being on schedule to deliver to Deft for color matching by the end of May.

<u>May Status</u>
Again, the focus was on balancing the trio of an acceptable appearance/gloss with an acceptable flexibility with acceptable resistance/weathering properties. BMS continued to explore new resin systems. The following quote is from the BMS report for May:

> "This month's focus on the UV-curable aerospace coatings project centered on fine tuning formulations for their flexibility and chemical resistance, and preparing samples for weathering studies. Four formulations with different combinations of hard and soft resins were formulated into coatings and sprayed onto the both chromated and non-chromated panels, and subsequently tested after curing. All formulations had acceptable gloss, chemical resistance, and flexibility, and panels of these coatings were placed into the weatherometer along with the two component control and stencil coatings. After 250 hours of accelerated weathering exposure, all four samples were observed to have ΔE values near 2, and chalking was also observed. Both the stencil and two component control had ΔE values less than 1."
>
> Deft and Bayer Material Science met to discuss the project's current progress, and it was concluded that the base resin formulation needed further development to address the chalking issue. Furthermore, it was also decided that a full evaluation needed to be performed on the final, color-matched coating to have the best chance of success."

At that time BMS determined that a schedule slippage to allow for the resin investigations would be necessary.

June Status

BMS reported that the new resins were continuing to show poor performance in accelerated weathering, exhibiting significant chalking and poor appearance after 500 hours. The revised timeline showed Deft color matching being completed by mid-October.

July Status

BMS continued to report problems balancing low gloss and flexibility, attempting a variety of additive solutions to adjust coating properties.

August Status

During August BMS focused on reducing the amount of color change and chalking during Xenon accelerated weathering, a problem that had not appeared in the 21BK001 coating but that was consistently appearing in the new resin formulations. The following quote is from the BMS report for August:

> "Over the past several months, our team has made substantial progress in gloss reduction, adhesion, and flexibility to the stencil formulation and our best current formulation meets or exceeds the two component polyurethane control coating in these performance areas. Upon accelerated weathering, the UV cured coatings developed an unexpected chalking issue that we believe needs to be addressed before further development occurs in order to have the highest probability for a favorable evaluation by the Air Force CTIO."

September Status

BMS reported, "In mid-August, Bayer passed off our best formulation to Deft for color matching/additional refining. During September, Deft has taken the major role in coating development while Bayer performed a supporting role by offering technical advice and shipping the resins needed for scale up." BMS reported the data table shown as Table 12 on the formulation being passed to Deft, referred to in their internal numbering as "Flat Black NB #974862."

Table 12. Data for coating Formula Passed to Deft

Properties of Flat Black NB #974862	
100 MEK Double Rubs	Passed
Flexibility	40% GE Impact
ΔE Color at 250 Hrs Accelerated Weathering	0.3 (no chalking)
ΔE Color at 500 Hrs Accelerated Weathering	0.6 (no chalking)
ΔE Color at 750 Hrs Accelerated Weathering	0.8 (no chalking)
ΔE Color at 1000 Hrs Accelerated Weathering	1.2 (no chalking)
Skydrol Resistance (24 hours)	Passed – No blistering or delaminating
DI Water Soak (24 hours)	Passed – No blistering
85° Gloss	15
Adhesion	5B (bare aluminum)
Pencil Hardness	H

The table above does not list the 60° gloss, but it was stated as being ≤5 units. The 85° gloss did not pass the requirement of 9, but CTC stated a willingness to engage with end users and secure a deviation from the specification for 85° gloss, as stakeholders verbally confirmed that the 85° requirement was considered of lesser importance. Data indicated that the coating balanced resistance, flexibility, and appearance properties that could meet performance requirements.

Deft Color Matching

After receipt of the coating formulation from BMS, Deft was to color match the coatings and provide samples for testing according to the JTP. Before submitting to external JTP testing, Deft conducted internal testing against MIL-PRF-85285 performance requirements. Color matching occurred in October and November 0f 2009, with samples shipped for spray-out and JTP testing in December. Data from Deft's internal testing are shown in Table 13.

Table 13. Deft December 2009 Testing to MIL-PRF-85285

		37038 Black	36173 Gray	36118 Gray
TEST	**SPECIFICATION**	**21BK003**	**21GY001**	**21GY002**
CURE TIME	Run and report	8 min	8 min	8 min
COLOR, GLOSS				
Color Delta E from Standard	< 1.0	0.51	0.45	0.95
60	5 MAX.	5.0	4.3	4.0
85	9 MAX.	9.0	9.0	8.0
ADHESION/STATE OF CURE				
TAPE RESISTANCE	8 HR. MAX. @ RT	pass	pass	pass
CONTRAST RATIO	95% MINIMUM (2.0 - 2.4 DRY MILS)	pass	pass	pass
MEK	25 DOUBLE RUBS	>50	>50	>50
DRY/WET ADHESION	4A/4B	4B/4B	4B/4B	4B/4B
FLEXIBILITY				
AMBIENT	40% MINIMUM	20%	40%	40%
COLD	-51C, 2" MANDREL	2"	2"	2"
WEATHERABILITY (500 HOUR XENON)				
60 DEG. GLOSS	5 MAX.	0.4	0.8	0.6
85 DEG. GLOSS	9 MAX.	2.6	3.4	2.7
Color Delta E from Standard	1.0 MAX	3.84	0.21	0.49
OTHER TESTS				
STRIPPABILITY, 500 hrs. Xenon	90% MINIMUM	100%	100%	100%
HEAT RESISTANCE	1 HR @ 250F., ΔE <1.0	0.10	0.47	0.40
HUMIDITY	30 DAYS	5A	5A	5A
FLUID RESISTANCE				
INITIAL	MAXIMUM 2 PENCIL DROP	2B	2B	2B
MIL-L-23699	24 HR @ 250 F.	B	2B	3B
MIL-H-83282	24 HR @ 150 F.	2B	2B	3B
JP-5	7 DAYS @ 77F.	4B	4B	4B

Both gray coatings demonstrated the ability to meet minimum performance criteria. The 21BK003 black coating demonstrated failures in flexibility and 500 hour weathering. However, Deft indicated that a final black version of the coating adhering more closely to the NB #974862 black formulation passed on by BMS could be produced and that these final coatings should proceed to JTP testing. The pencil hardness of the coating was a concern, as 2B was below the target value of HB or better. However, there is no mil-spec hardness requirement for coatings as long as resistance properties are met.

CTC Cure Testing

In preparation for the JTP testing and proposed demonstration, CTC requested and received a sample of the 21BK003 for cure testing at CTC's facility in Johnstown, Pennsylvania. The purpose of this testing was to better determine how coating might cure at varying UV intensities and exposure times to simulate variation that might occur in a maintenance environment. In addition, CTC evaluated cure of the coating with the Cure-Tek 2400W lamp system, a modified version of the Cure-Tek 1200W in which two 1200W lamp heads with two power supplies were placed on a flexible frame to double the cure area provided by the Cure-Tek 1200. The Cure-Tek 2400W was to be utilized in applying coatings for the field demonstration after competition of the JTP testing. Figure 13 shows the Cure-Tek 2400W in operation.

Figure 13. Cure-Tek 2400W in Operation

This cure testing was conducted on November 18-19, 2009. MEK rub testing showed successful cure of the 21BK003 coating as both a topcoat and a marking coating at varying intensities and stand-off distances from the substrate. The coating appeared to cure as fast as four minutes in some cases, which was less than the BMS/Deft recommended time of 8 minutes cure. In a follow-up discussion with BMS personnel, it was cautioned that while a shorter exposure period seems to cure the coating, coating that passes the MEK rub test may still not be fully cured.

A full description of the November 2009 testing and results can be found in Appendix D, Cure-Tek 2400W Cure Testing.

6.2.2 JTP Testing of BMS/Deft Flat Formulations

JTP testing on the BMS/Deft 21BK003, 21GY001, and 21GY002 was conducted at Battelle Memorial Institute in Columbus, Ohio. The initial spray-out and cure occurred on December 14-17, 2009 utilizing a H&S Autoshot Cure-Tek 1200W lamp system. Coating and cure were supervised by CTC. At that time a vertical spray-out revealed that the coatings had no sag resistance. “Sag resistance” is the terminology used to indicate the ability of the coating to cling to a vertical surface while awaiting cure. Sag resistance is not a mil-spec property; however, it is a practical requirement for painting aircraft and aircraft components with coatings that will not cure without UV exposure. The original 21BK001 coating had displayed acceptable sag resistance but the property was lost at some point during the development process. All future evaluations of UV-curable coatings took this requirement into account.

In addition, the Deft 21GY002 (FED-STD-595 color 36118) showed a severe pigment float problem and was obviously far off the required color match. The 37038 black and 36173 gray coatings were reapplied and cured on a horizontal surface, with the statement from Deft that future batches would include anti-sag agent. Deft created a new batch of 21GY002 with the coating float problem corrected and anti-sag agent added. It was sprayed and cured at Battelle in January.

Results

From March 2010 through May 2010, the results of the JTP testing were reported by Battelle. In virtually no property did all of the three coatings provided by BMS/Deft match the requirements of the JTP specification. Results for tests comparable with the stencil coating are summarized in Table 14.

Table 14. Summary of Flat BMS/Deft JTP Test Results

Property Tested	36173 Gray	36118 Gray	37038 Black
Color	Pass	Fail	Pass
Gloss at 60° & 85°	60° = pass 85 = ≤15	60° = pass 85 = pass	60° = pass 85 = ≤15
Adhesion	Fail	Fail	Fail
Stencil Adhesion on APC	Pass	Fail	Fail
Pencil Hardness	Pass	Pass	Pass
GE Impact Flexibility	20% (fail)	10% (fail)	40% (pass)
Fluid Resistance			
Lube Oil (24 hrs)	Fail	Fail	Fail
Lube Oil (7 days)	Pass	Pass	Pass
Hydraulic Fluid Resistance (24 Hr.)	Pass	Pass	Pass
Jet Fuel (7 day)	Fail	Fail	Pass
Jet Fuel (30 day)	Fail	Fail	Fail
Skydrol (30 day)	Coating stripped	Fail	Fail
Deionized Water (30 day)	Fail	Fail	Pass
Heat Resistance			
500 hrs weathering**	Pass	Pass	Pass
3000 hrs weathering	Fail	Fail	Fail

Full details on all the test results, including coating thicknesses, optimal performance criteria test results not included in Table 14, and a detailed analysis and discussion of each test is included as Appendix E, JTP Test Data from BMS/Deft Flat Coatings. High-level discussion and conclusions were as follows.

The failure to pass basic adhesion tests and variation observed in adhesion data called much of the other test data into question. If the coating is not achieving proper adhesion to act as a barrier coating in the first place, failure to pass resistance tests is likely. Multiple teleconferences with Deft and BMS were held to discuss the data, with one suggestion being that the thickness of the applied coatings in the Battelle testing (typically 1 or more mils above specification) had hindered coating through-cure and prevented the samples from achieving the best-possible properties. However, this assertion remained unproven.

Regarding other critical properties, a 20% flexibility was equivalent to that reported by the control coatings despite qualification of the control coatings to a mil-spec requiring 40%. This finding indicated a potential for retest of the flexibility requirement yielding better results. However, the accelerated weathering data showed potentially problematic results. Although the UV-curable coatings met the gloss and color change requirements at 500 hours, they showed chalking and gloss loss indicating damage to the coatings. Though they passed specification requirements, the PI indicated dissatisfaction with a coating showing this performance. The revelation that a coating can pass the gloss requirements after accelerated weathering while still presenting an unacceptable military appearance indicated that in future trials a minimum gloss change requirement should be established rather than the base specification requirement that gloss remain below a certain value. This minimum would enable a numerical value to be placed on “damage to the coatings” evaluation during weathering.

6.2.3 July 2010 Application Trial at OO-ALC

A full description of the observations, discussions, and conclusions drawn from the attempt to conduct a field Demonstration/Validation of the BMS/Deft coatings can be found in Appendix F, Trip Report For July 2010 Visit to OO-ALC. The visit and its outcomes are summarized briefly here.

<u>Background</u>
A visit to Hill AFB was carried on July 12 to July 15, 2010. There were multiple purposes for this visit. The first purpose was to conduct an in-person meeting with representatives from BMS, Deft, H&S Autoshot (the lamp manufacturer), and the ESTCP Principal Investigator. During the meeting the results of the Battelle testing could be discussed and a decision made how to proceed. If a convincing case could be made that the results of the Battelle testing were due to application error, the second purpose was to conduct a real-world demonstration of coating application and cure on target F-16 and C-130 aircraft.

<u>Coatings Evaluated</u>
For this demonstration, Deft had created new batches of each of the three coating colors. These new batches were altered from the samples tested at Battelle by addition of an anti-sag agent and a new dispersant to eliminate the coating float problem observed with the 36118 gray.

Lamp Utilized
A double-headed 2400W Cure-Tek lamp was brought on site for the demonstration. This lamp consisted of two 1200W lamp heads and power supplies placed on a single flexible frame. The intensity and spectral output are identical to that of a Cure-Tek 1200W lamp, but use of two lamp heads allows the illuminated cure area to be doubled.

Depot Demonstration
To settle the question of how the coatings would perform in a real world spray-out situation before attempting an on-aircraft demonstration, the PI had all three coatings sprayed on an “A-Frame” coated with aerospace primer on one side and a primer/topcoat stack-up on the other. These were the same coating stack-ups utilized in previous tests, but this time on a large structure rather than small aluminum panels. This A-frame effectively simulated the coating stack-ups on a real aircraft which the Deft coatings would be used as either topcoats or stencil coatings. The plan was to spray the coatings and then conduct hardness and adhesion tests before proceeding to a potential on-aircraft demonstration.

Results
None of the Deft coatings were able to achieve cure on the A-frame, remaining tacky and uncured despite extended exposure to the Cure-Tek 2400W light. This finding proved correct whether the coatings were used as topcoats or stencil coatings.

6.2.4 Demonstration Failure Recovery Analysis and Testing

After the failures during JTP testing and during the attempted demonstration at OO-ALC, an extended effort was made to determine what had caused the cure failure, with multiple laboratory tests conducted at CTC, Deft, and BMS to duplicate the results. The investigation and proposed solutions are documented below.

6.2.4.1 Objective

Deft Finishes had three UV-curable topcoats with the potential for use in USAF aerospace maintenance operations. However, in performance testing at Battelle Memorial Institute, the coatings failed many of the minimum requirements for use as aerospace topcoats. Furthermore, the results of the tests were inconsistent, with varied results between each of the three topcoats. In some cases results varied even between two tests of the same coating. Finally, the coating batches prepared for a demonstration at OO-ALC appeared to have been affected by unknown factors preventing a full and complete cure.

The objective of the recovery analysis and testing was to determine why the UV-curable formulations for each of the three colors could not consistently meet JTP performance requirements, provide an explanation for the unknown factors preventing curing of the coating batch applied at OO-ALC, and alter the formulation and/or application procedures to prevent both problems from reoccurring.

6.2.4.2 Evaluation Parameters

This section details the efforts to meet the objectives of the recovery plan. The first stage was Root Cause Identification to determine the cause of the coating failures. The second stage was Confirmation Testing to ensure that the new coating batches from Deft corrected the problem. Upon success of these stages, a cure ladder study of the effect of varying UV exposures and a repeat of the JTP testing would have been conducted.

6.2.4.2.1 Root Cause Identification

On July 14-15, 2010 a Demonstration/Validation was attempted at OO-ALC using the three UV-curable topcoat colors provided by Deft Coatings; 21GY001, 21GY002, and 21BK003. The attempt failed due to the fact that the coating would not achieve full cure. For all three colors, the coating remained soft and tacky even after extended UV lamp exposure. After extensive testing, Deft identified the dispersant used in the formulation as the primary cause of failure.

<u>History of Formulation Change</u>
In November 2009, coating spray-outs were made at Battelle Memorial Institute for the planned JTP testing. The 21GY002 coating was the first coating to be sprayed, and there were major application problems. The coating was applied to substrates hanging vertically, and the coatings on these panels began to sag and drip before coating cure was effected, ruining the panels for testing purposes and depleting the supply of coating. In addition, the 36118 gray suffered from pigment float where the blue pigment quickly separated out from the coating, even shortly after mixing. To address these concerns, Deft mixed a new batch of the 21GY002 for JTP testing with formulation modifications. The 21GY001 and 21BK003 coatings were applied as-is on horizontally positioned panels to prevent coating sag, but future batches of these coatings had the same formulation changes made.

<u>Post-Dem/Val Failure Analyses</u>
After the July Dem/Val, Deft was unable to reproduce the coating failure in the Deft laboratory. These attempts were made using "retain" samples that were from the same batches prepared for the Hill Dem/Val. These batches are identified in Table 15.

Table 15. Batch Numbers of samples

Deft Identification	Color	Batch Number
21GY001	36173 Gray	200-63
21GY002	36118 Gray	200-64
21BK003	37038 Black	200-65

Each batch had been split into samples at the following locations:

1. Hill AFB (These samples were used in attempted demonstration.)
2. CTC (These samples were shipped directly from Deft to CTC after batch formulation and later shared with Bayer Material Science.)

3. Deft (these “retain” samples were kept at Deft after creation of the batch).

Initially, Deft could not reproduce the failure on their retain samples, though the results were reproduced with the CTC samples at both CTC and Bayer. This caused some confusion, as all samples from the same batch should have been identical. It was concluded that either:

1. Something had happened to both the Hill AFB and CTC samples in transit or;
2. Something differed between the application and cure procedure used by Deft and those followed at CTC, Hill AFB, and Bayer.

The theory that something had happened to the samples in transit was considered unlikely, as the samples sent to Hill AFB and the samples sent to CTC were shipped separately. It seemed unlikely that the same event had occurred to both samples. Most of the focus was placed on comparing factors differing factors in the application and cure process. Among those tested were:

1. Substrate temperature
2. Coatings used in stack-up and time since coating application
3. Freeze-thaw stability
4. Intensity of UV exposure

Initially none of these factors were able to explain the differing results. The results of the factors testing are detailed in Appendix G, Root Cause Analysis Testing. During this testing, pencil hardness and MEK rub were agreed upon as the two tests to determine a coating’s successful state of cure. Overall, the results seemed to show that some factors such as a heated substrate surface and more intense UV exposure could improve the pencil hardness of the final cure, but none of the results seemed to produce coatings that performed as per previous testing of samples formulated at Deft and Bayer.

In the interim the samples from Hill AFB were shipped back to Deft for comparison testing. Deft also obtained a 1200W Cure-Tek lamp and Solarlight UVA radiometer. Previously Deft had used the Cure-Tek 400W lamp to cure their coating. In this same time period, Deft began to notice worsening performance from the retain samples, as if they were gradually destabilizing. “Micro-voids” were observed in the coating surface under magnification. At first this phenomenon was observed in freeze-thaw stability testing samples, which showed notably lower pencil hardness than samples not subjected to freeze thaw. However, the micro-voids were also detected in samples that did not undergo freeze-thaw, suggesting that the freeze-thaw testing was accelerating a reaction that was already occurring.

With the new lamp and meter, Deft was able to reproduce the UVA exposure that the coating samples were receiving at Hill, Bayer, and at CTC. When the retains and samples from Hill were compared at the same UVA exposures, Deft was able to reproduce the coating failures.

This reproduction is shown in Table 16. The 4B and 5B hardness readings are unacceptable and they exemplify a failure to achieve proper cure.

Table 16. Exposure Intensity Effects on UVA Topcoats from July Dem/Val

Sample ID	UVA Intensity	Pencil Hardness	MEK Resistance (Double Rub)	Notes
21BK003(D)	32.5 mW/cm^2	5H	>50	Deft Retain
21BK003(H)	32.5 mW/cm^2	5H	>50	Hill AFB
21GY001(D)	32.5 mW/cm^2	5B	46	Deft Retain
21GY001(H)	32.5 mW/cm^2	4B	25	Hill AFB
21GY002(D)	32.5 mW/cm^2	5B	10	Deft Retain
21GY002(H)	32.5 mW/cm^2	5B	10	Hill AFB
21GY002(D)	50 mW/cm^2	5B	30	Deft Retain
21GY002(H)	50 mW/cm^2	5B	42	Hill AFB
21GY002(D)	71.5 mW/cm^2	4H	>50	Deft Retain
21GY002(H)	71.5 mW/cm^2	4H	>50	Hill AFB

For comparison, the mW intensity recorded from the lamps during the July Dem/Val was reported as 23 to 25 mW. Additionally, note that the tests shown in Table 16 were carried out with the UV-curable topcoats applied to unprimed panels. Experience suggested that UV-curable coating on unprimed panels can cure completely and with less UV exposure than a topcoat painted on a primer. The unprimed surface explains why cure and high pencil hardness was achieved on the 21BK003 at 32 mW/cm^2 when no such cure could be achieved at Hill AFB using only a slightly lower intensity. The sole instance of successful cure at Hill AFB was with 21BK003 on an unprimed panel.

The results in Table 16 indicate that the Hill AFB and retain samples were showing essentially the same cure properties. Furthermore, they did not match previous experience with the coating, where coating cure at HB and harder could be achieved even on primed panels at 30mW/cm^2. Deft instituted testing of past retains and found that retains mixed before the addition of the new dispersant and rheology modifier universally showed better performance and none of the micro-voids were observed under magnification in the 200-63, 200-643, and 200-65 batches. This firmly identified one or both of these additions as contributing to coating failure.

The use of high UVA intensities in the Deft laboratory, as well as the fact that many of the tests were carried out on unprimed panels using the 21BK003 black, had helped mask the problem during early Deft testing on the retain samples. Under those circumstances, Deft was able to achieve cure even with the microvoid effect of the degraded coating. Use of a UVA intensity more closely approximating what was used in the field allowed the problem to be identified.

Comparison to Original 21BK001 Coating

The 21BK001 coating is the so-called “stencil coating” that was used as the basis for this effort and was demonstrated on two aircraft. A sample was available from the original prepared formulation. Deft sprayed some 21BK001 for comparison, and noted that there was a pigment settling problem that required an hour on the paint shaker to achieve dispersion. Even after spray, the texture of the coating was uneven and rough. However, a full cure was achieved.

Deft provided the following list to explain how different the 21BK001 in the screening testing was from the latest 21BK003 formulation.

- The 2 urethane acrylates used are different
- Different flattening agent used
- Different photointiators used (same wavelength absorbance and concentration, two separately instead of one mixture)
- Different iron oxide pigment
- Different extenders
- Different anti-settling agent
- Used to contain HAPs; now eliminated
- Maybe three ingredients the same

6.2.4.2.2 Dispersant and Rheology Modifier Testing

Deft had tested each coating batch before shipping it out and had not encountered the cure problems discussed above. It was theorized that the coating degraded over time, meaning that samples tested immediately after batch creation would perform well. To test this theory and to identify whether the rheology modifier or the dispersant or both was responsible for the coating degradation, new samples were formulated and tested at separate time intervals from formulation. Testing occurred for all samples on October 6, 2010, meaning the samples had been prepared between three weeks and one day before testing. The results are shown in Table 17, with red PH readings indicating a result considered a failure. These panels were painted on a primed substrate.

Table 17. Raw Material Effects Over Time

Sample ID	Date Formulated	UVA Intensity	Pencil Hardness	MEK Resistance (Double Rub)	Notes
21GY002(V13)	9/27/10	50 mW/cm^2	5H	>50	New Rheology Modifier
21GY002(V13)	10/5/10	50 mW/cm^2	B	30	New Rheology Modifier
21BK003(V19)	9/15/10	32.5 mW/cm^2	3H	>50	Dispersant Changed
21BK003(V19)	10/5/10	32.5 mW/cm^2	3H	>100	Dispersant Changed
21BK003(V20)	9/16/10	32.5 mW/cm^2	5H	>50	Rheology Modifier Omitted
21BK003(V20)	10/5/10	32.5 mW/cm^2	B	27	Rheology Modifier Omitted
21BK003(V21)	9/21/10	32.5 mW/cm^2	5H	>50	New Rheology Modifier
21BK003(V21)	10/5/10	32.5 mW/cm^2	B	30	New Rheology Modifier

The results show that only coatings with a new dispersant were able to achieve proper cure. This identified the dispersant as the problem. The "shelf life" of coatings formulated with this dispersant appear to be much shorter than formulations with other dispersants, which had been successfully cured when applied over six months after formulation..

6.2.4.3 Deft Root Cause Solution

Deft reformulated new batches of all three coating colors with an alternative dispersant based on the Version 19 formulation identified in Table 17. Samples of these new coating formulations were subjected to confirmation tests at both Deft and CTC. The batch numbers of the new formulations are shown in Table 18.

Table 18. New Coating Batch Numbers

Deft Identification	Color	Batch Number
21GY001	36173 Gray	156-78
21GY002	36118 Gray	156-77
21BK003	37038 Black	156-76

6.2.4.3.1 Deft Confirmation Testing

Initial confirmation testing was conducted at Deft during production of the new coating batches. After the formulation of the Version 19 21BK003 Black, Deft conducted a cure ladder study on the effects of different UV exposure intensities on hardness. Table 19 shows the results.

Table 19. UV Intensity Effect on Hardness

Run #	Exposure Intensity mW/cm^2	Pencil Hardness	MEK Resistance Double Rubs
1	20	B	24
2	20	B	34
3	30	HB	116
4	40	H	192
5	40	H	196
6	50	2H	300
7	60	3H	371
8	60	3H	375

Based on the results obtained from this study, Deft recommended a minimum exposure intensity of 30 mW/cm^2 to ensure that the required physical performance properties would be achieved in the 37038 color topcoat. In the remaining testing, Deft cured test panels under a 1200W H&S Autoshot Cure-Tek lamp system, with a UVA exposure of no less than 40mW/cm^2 for ten minutes, as measured by a SolarLight radiometer. As per the JTP, the coating was applied with the required primer layer (unless a specific test required no primer) at the required thickness, on the required substrate.

Deft's internal testing results for 21BK003, 21GY001, and 21GY002 are shown in the tables below. All Samples were exposed on the UVA 1200W lamp to an average energy of 58 mW/cm^2 for 10 minutes. A 15-minute flash-off time for the UV-curable topcoat was allowed between topcoat application and cure. The primer used was Deft 02Y40B at a thickness of 1.2-1.3 mils, with 4 hours between primer application and topcoat application.

Table 20. Deft 21BK003 Testing at Selected Thicknesses

DFT (mils)	Pencil Hardness	MEK Resistance Double Rubs	Cross Hatch Adhesion	Cross Hatch Adhesion(wet)
1.6-1.9	F	78	4A/4B	
1.3-1.5	F	90	4A/4B	4A/4B
1.4-1.6	F	100	4A/4B	
2.2	F	300	4A/4B	
1.9-2.1	H	236	4A/4B	
2-2.3	H	103	4A/4B	4A/4B
2.1-2.3	H	200	4A/4B	
1.9-2.1	F	113	4A/4B	
2.5-2.6	H	200	4A/4B	
2.4-2.9	F	300	4A/4B	4A/3B
2.4-2.8	F	>300	4A/4B	
3.5	H	>300	4A/3B	
3.3-3.8	F-H	>300	3A/3B	4A/4B
3.5-3.8	H	>300	4A/3B	

Table 21. Deft 21GY001 Testing at Selected Thicknesses

DFT (mils)	Pencil Hardness	MEK Resistance (double rubs)	Cross Hatch Adhesion	Cross Hatch Adhesion(wet)
1.85-2.0	F	>50	4A/4B	4A/4B

Table 22. Deft 21GY002 Testing at Selected Thicknesses

DFT (mils)	Pencil Hardness	MEK Resistance (DR)	Cross Hatch Adhesion	Cross Hatch Adhesion(wet)
2.0-2.2	HB	>50	4A/4B	3B/3A

6.2.4.3.2 CTC Confirmation Testing

CTC conducted screening testing for the reformulated UV-curable coatings as both topcoats and stencil coatings. For the stencil adhesion testing, the UV-curable topcoats were applied to a layer of Deft topcoat meeting MIL-PRF-85285 Type IV, which had been allowed 24-hour cure before UV-curable coating was applied as an additional coating layer. The topcoat had been applied to a Sherwin Williams primer, which meets MIL-PRF-23377 Type I, Class C2. The primer had been allowed 48 hours cure before application of the topcoat.

A variety of coatings meeting MIL-PRF-23377 were used for the required primer layer in CTC topcoat testing of the 21BK003 black. After comparison of the results from different primers, topcoat testing of the 21GY001 and 21GY002 was conducted solely using the Deft primer 02Y40B.

All panels were coated with the UV-curable coating approximately 4 hours after primer application and exposed to an average 58 mW/cm2 UVA for 10 minutes. Table 23 shows the pencil hardness, ASTM D3359 Method A & B results for the panels tested.

Table 23. 21BK003 Topcoat Hardness and Adhesion

Sample ID	Primer Type	Primer DFT (avg)	Flash Time	UV DFT (avg)	Pencil Hardness	ASTM D3359 Meth A	ASTM D3359 Meth B
4839	SW[1]	0.9 mil	10 min.	2.1 mils	H	4A	4B
4840	SW	0.75 mil	10 min.	2.2 mils	H	4A	3B/4B
4849	SW	0.85 mil	15 min	2.3 mils	H	4A	4B
4853	SW	0.8 mil	15 min	2.3 mils	H	4A	3B/4B
4760	02Y040A[2]	0.9 mil	10 min	2.3 mils	H	4A	4B
4762	02Y040A	0.9 mil	10 min	1.8 mils	H	4A	4B
4874	02Y040B[3]	1.3 mil	10 min.	1.9 mils	H	4A	4B
4876	02Y040B	1.0 mil	10 min.	1.9 mils	H	4A	4B
4869	02Y040B	1.1 mils	15 min.	2.0 mils	2H	5A	4B
4870	02Y040B	1.1 mils	15 min.	2.1 mils	2H	4A	4B
4860	02Y040B	1.1 mils	15 min.	3.3 mils	H	4A	3B
4862	02Y040B	1.1 mils	15 min.	3.1 mils	H	4A	3B/4B

1 Sherwin-Williams primer meeting MIL-PRF-23377
2. Deft Primer
3. Deft Primer

Table 24 shows the wet tape adhesion results for 21BK003.

Table 24. 21BK003 Wet Tape Adhesion

Sample ID	Primer Type	Primer DFT (avg)	Flash Time	UV DFT (avg)	ASTM D3359 Method A after 24 hours water exposure
4736	SW	0.6	10 min	3.0 mils	4A
4737	SW	0.6	10 min	2.8 mils	4A
4738	SW	0.6	10 min	3.2 mils	4A/5A

21BK003 samples tested on 02Y40B primer passed 100 MEK double-rubs and the sag test without difficulty. Table 25 shows the results when 21BK003 was tested as a stencil coat.

Table 25. 21BK003 Stencil Coat Adhesion

Sample ID	Primer DFT (avg)	Topcoat DFT (avg)	UV DFT (avg)	ASTM D3359 Meth A	ASTM D3359 Meth B
S1	0.8	1.8	2.30	5A	_
S2	0.8	1.5	2.40	4A	4B
S3	0.6	1.6	2.20	4A	_

The UV-cure colors were then tested as topcoats according to the same procedure where the panels were coated with the UV-curable coating approximately 4 hours after primer application and exposed to an average 58 mW/cm2 UVA for 10 minutes. In all cases, Deft 02Y40B primer was used. In all cases, a 15-minute flash time was allowed after UV topcoat application before UV cure. Two ranges of thicknesses were tested. The first was the mil-spec required range of 1.7 to 2.3 mils. This thickness has proven to be almost impossible to achieve during application in the field, and a more realistic thickness of 2.4 to 3.5 mils was evaluated to determine the likely performance of coating in the field. A summary of the results is shown in Table 26.

Table 26. CTC Confirmation Testing Results

Thickness Range 1.7-2.3 mils		21BK003 37038 Black		21GY002 36118 Gray		21GY001 36173 Gray	
Test	**JTP Requirement**	**Avg. Result**	**Pass/ Fail**	**Avg. Result**	**Pass/ Fail**	**Avg. Result**	**Pass/ Fail**
Adhesion	4A or 5A	4A	Pass	2A	Fail	4A	Pass
Wet-Tape Adhesion	4A or 5A	4A	Pass	0A	Fail	4A	Pass
Pencil Hardness	2B or harder	2H	Pass	HB	Pass	HB	Pass
MEK Rub	>25 Double Rubs	>100	Pass	>100	Pass	>100	Pass
Sag Resistance	>4 hours no sag	>8 Hours	Pass	>8 Hours	Pass	>8 Hours	Pass
Stencil Coat Adhesion	4A or 5A	4A	Pass	4A	Pass	NA	NA
Thickness Range 2.4-3.5 mils		**21BK003 37038 Black**		**21GY002 36118 Gray**		**21GY001 36173 Gray**	
Test	**JTP Requirement**	**Avg. Result**	**Pass/Fail**	**Avg. Result**	**Pass/Fail**	**Avg. Result**	**Pass/Fail**
Adhesion	4A or 5A	4A	Pass	*	Fail	0A	Fail
Wet-Tape Adhesion	4A or 5A	4A	Pass	*	Fail	0A	Fail
Pencil Hardness	2B or harder	H	Pass	*	Fail	2B	Pass
MEK Rub	>25 Double Rubs	>100	Pass	*	Fail	> 100	Pass
Sag Resistance	>4 hours no sag	>8 Hours	Pass	>8 Hours	Pass	>8 Hours	Pass
Stencil Coat Adhesion	4A or 5A	4A	Pass	4A	Pass	NA	NA
*** Coating delaminated from panels at this thickness, could not test properties.**							

Two examples of adhesion failure approximately 1 mil thick for 21GY002 are shown in Figure 14.

Figure 14. 21GY002 Adhesion Testing at 1 mil thickness

Two examples of adhesion failure approximately 2 mils thick for 21GY002 are shown in Figure 15.

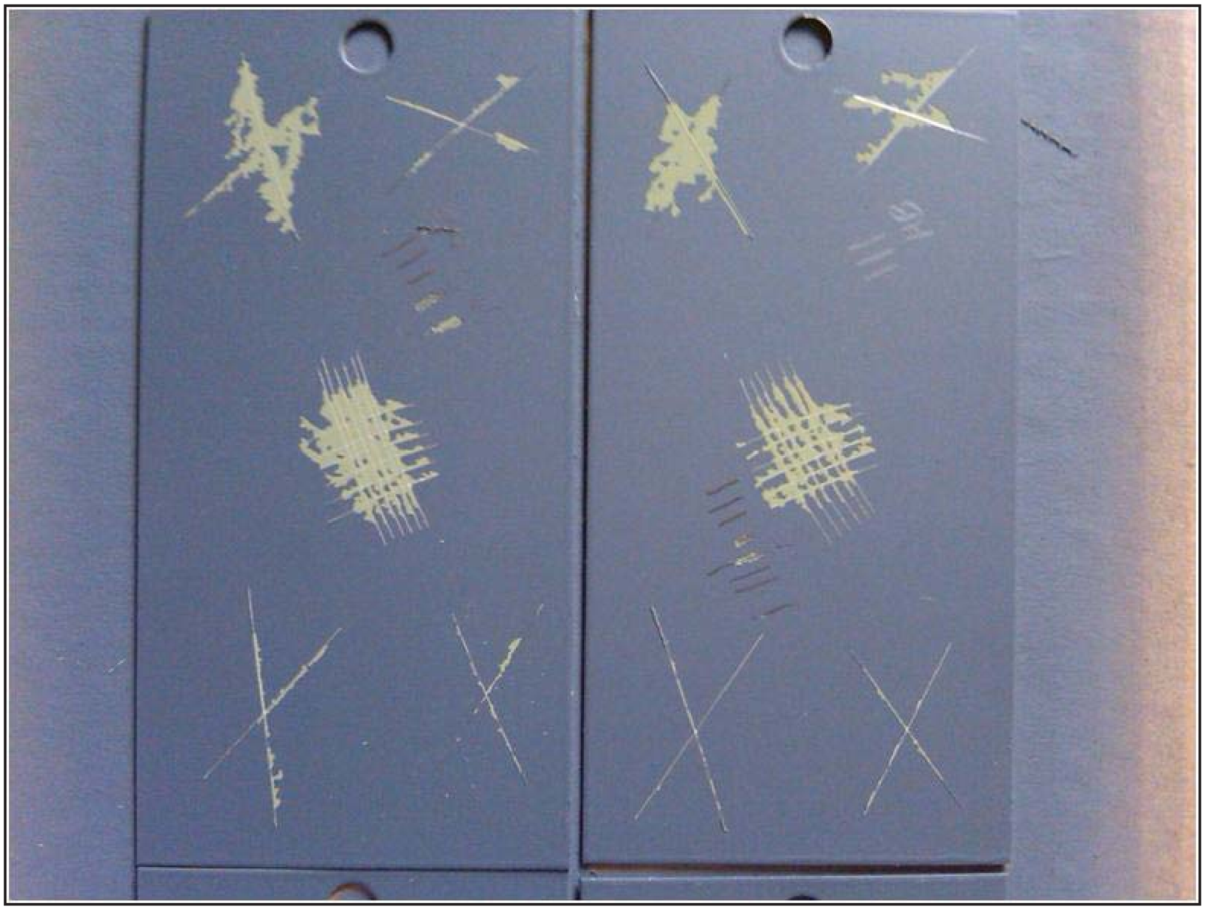


Figure 15. 21GY002 Adhesion Testing at 2 mil coating thickness

The 21GY002 was also applied and cured at a DFT thickness of approximately 3 mils. However, at this thickness the coating experienced a massive wrinkling effect during UV exposure that made it impossible to test, or even to measure an average DFT. Figure 16 shows the 21GY002 at approximately 3 mils of thickness.

Figure 16. 21GY002 at 3 mils thickness

<u>Conclusions</u>

Subsequent discussion with Deft indicated that 4 hours might have been insufficient time for primer cure before painting with the UV-curable topcoat due to the fact that a cured UV-curable topcoat hinders any further solvent outgassing from the primer. This is in contrast to currently used primers at OO-ALC, to which topcoats are applied after only four hours. A subsequent test with a longer primer wait time improved some of the catastrophic failures, but the gray coatings still showed adhesion failures at over 2.5 mils.

After discussion with the project stakeholders and the task PI, a decision was made that the BMS/Deft coatings had proven too unreliable and sensitive to various application and cure issues to ever be effective in a maintenance environment. The black coating showed more promise than the grays, but use of flat black is relatively limited and it is unlikely that any installation would implement the equipment and organization required for UV-curable coatings for a single color. With the agreement of the task PI, further testing and attempts to implement the BMS/Deft coatings were discontinued.

6.3 BMS/Deft Gloss White Coating Performance Results

As discussed in Section 5.1.3, from January through December 2010, the BMS/Deft partnership attempted to formulate a UV-curable coating meeting aerospace requirements that would satisfy the gloss white requirements for FED-STD-595C 17860 and 17925.

6.3.1 BMS/Deft Initial Gloss White Coating Internal Development and Testing Effort

January Status

BMS/Deft accomplished the following in January:

- Developed initial formulations based on using UV-PUD as the base polymer and formulated to give as high of gloss as possible were evaluated.
- Identified and ranked critical performance tests were in the order of most difficult to pass for a waterborne UV curable:
  1. Gloss
  2. Water resistance
  3. Weathering (specifically gloss requirement)
  4. Chemical resistance
  5. Adhesion
  6. Flexibility
- Determined all coating evaluations must be performed using spray applications, as the gloss measurements of panels prepared using a drawdown applicator and those prepared using spray applications were notably different.
- Performed a photoinitiator study to determine the initiator that yielded the best gloss while maintaining chemical resistance. Waterborne coatings limit the photoinitiator selection available since a majority of photoinitiators have limited solubility in solvents that are compatible with PUDs
- Performed additive and pigment study to evaluate compatibility and ability to increase gloss. A thickener and defoamer were identified as being compatible and a pigment paste was identified to produce the highest gloss.
- Identified the humidity resistance test as challenging for these systems.

February Status

BMS/Deft accomplished the following in February:

- Developed optimized formulation that rendered acceptable hiding.
- Evaluated different crosslinkers, polycarbonate diol based PUDs, and additives for their ability to increase the gloss and/or water resistance. Results indicated that the only coating to pass the 30 days in the Cleveland condenser (water resistance resting) was the formulation without additives, crosslinkers, or polycarbonate PUDs.

March Status

BMS/Deft accomplished the following in March:

- Identified the optimum levels of pigment to maximize hiding and gloss through a ladder study.
- Evaluated flow and leveling additives enhance the gloss levels, but did not perform as expected and resulted in panels having lower gloss and water sensitivity issues. Water soluble crosslinkers were also evaluated and were found not to enhance performance or aesthetics.

April Status
BMS/Deft accomplished the following in April:

- Evaluated dispersants for optimal compatibility. The highest gloss dispersants and dispersant concentrations were identified, and these coatings were evaluated for their physical properties. No major physical properties differences were identified between the dispersants.
- Determined that the PUD dispersion coatings have increased water resistance four days after cure. This can be attributed to the neutralizing agent of the polyurethane dispersion evaporating, making the film more hydrophobic.
- Evaluated several water soluble crosslinkers and polycarbonate PUDs for enhanced water resistance. None of the monomers/polymers were effective at reducing water sensitivity and reduced the gloss of most systems.

May Status
BMS/Deft accomplished the following in May:

- Determined that adhesion loss occurred after curing the resin indicating the change in hardness causes a lack of adhesion. Determined best additive to improve adhesion use of particular pigment paste.
- Found gloss levels can be increased by using a synergist in the formulation that yields increased compatibility.
- Examined spray gun variables to see if higher gloss could be obtained by optimizing the spraying conditions. It was found that the gloss of the drawdown was the highest gloss that could be achieved from spraying at the correct conditions, and optimized spray conditions were identified.
- Carried out accelerated weathering testing indicating that the gloss reduction will not be an issue. However, the color change could be problematic.

June Status
BMS/Deft accomplished the following in June:

- Addressed the issue of yellowing upon heating by studying various photoinitiator packages, identified the most compatible rheology modifier, and discovered issues with film formation when sprayed in high temperature / high humidity environments.
- Studied enhancement of gloss and hardness by mixing with a small particle size polyurethane dispersion, however, the enhancements in the aforementioned properties came at the expense of the flexibility.

- Identified a photoinitiator package that yielded a ΔE = 0.8 upon heating at 120°C for one hour and passed the MEK double rub test. This photoinitiator package will need to be further tested for jet fuel resistance. Jet fuel resistance was found to soften the gloss white coating, while the other fluids have little impact on the coating's physical properties.

July Status
BMS/Deft accomplished the following in July

- Screened 8 different thickeners and identified best candidate.
- Conducted weathering testing showing ΔE = 0.76 after 1500 hours, but a gloss drop to 57 at 60°
- Prepared gloss white screening test panels for CTC testing

6.3.2 CTC Screening Testing on BMS/Deft Gloss White

After seven months of development, BMS's internal testing indicated that their gloss white formulation would meet many performance requirements. Past experience suggested that in many cases, UV-curable coating development shows that results in developer and manufacturer laboratories are not always achievable elsewhere. Therefore CTC conducted preliminary screening testing of the gloss white UV-curable formulation prior to the formulation being completed and finalized. This allowed feedback on the performance properties of the coating as tested in an independent laboratory prior to formulation activities being completed. Screening testing was conducted on the late-stage developmental gloss white UV-curable PUD formulation. The purpose of the screening testing was to determine the potential of the coating to move forward to full-scale performance testing.

6.3.2.1 TEST SAMPLES

The formulation tested, NB# 986095 was sprayed and cured on August 11, 2010 at the BMS office in Pittsburgh, Pennsylvania. The coating stack-ups created and the cure parameters are detailed below.

6.3.2.1.1 Coating Stack-Ups

Two coating stack-ups were utilized:

1) *Topcoat and Primer*:
    a. Gloss white formulation NB# 986095 over
    b. Deft 02Y40B primer, qualified to MIL-PRF-23377 Type I Class C2 on
    c. a 3" x 6" x 0.032" unclad aluminum 2024-T3 panel treated with a conversion coating conforming to MIL-C-5541, class 1A

2) *Flexibility Specimen*:

a. Gloss white formulation NB# 986095 over
b. a 3” x 6” x 0.032” unclad aluminum 2024-O panel, chromic acid anodized in accordance to MIL-A-8625, Type 1

For Topcoat and primer specimens, the conversion coating was applied approximately 16 hours before application of the primer. The primer was applied 3 to 4 hours before application and cure of the topcoat.

6.3.2.1.2 Cure Parameters

The NB# 986095 topcoat was cured using a Cure-Tek 1200W UVA lamp system at an 8 inch stand-off distance for an exposure time of 8 minutes. However, CTC’s testing has demonstrated that there is considerable difference in cure intensity within the effective cure area under an H&S lamp system. In order to correctly approximate how coating cure will occur in the field, two separate curing areas in the exposure area were identified to represent the optimum and minimum cure energy received when using the lamp. These optimum and minimum cure areas are identified in Figure 17, UV Exposure Intensity.

34.82	47.85	50.22	38.03
30.32	43.96	45.71	34.29
30.53	44.01	45.71	34.07
33.15	45.29	48.61	36.7

Figure 17. UV Exposure Intensity

The numbers shown above represent the mW/cm^2 UVA intensity measured with a Solarlight UVA radiometer. The magenta area measures 40 mW or more of exposure and is considered to be the optimum exposure area. The green area is between 30 and 40 mW and is considered to be the minimum exposure area.

Panels were created utilizing cure in both the optimum and minimum cure area. These were identified as a suffix to the coating stack identification, as listed below:

i. **-Opt**(imum) - Panels were placed in the red portion of the cure area at 8” stand-off and exposed to UV light for 8 minutes.

ii. **-Min**(imum) - Panels were placed in the yellow portion of the cure area at 8” stand-off and exposed to UV light for 8 minutes.

By way of example, a particular stack-up/cure combination might be referred to as “*Topcoat and Primer – Min*”.

6.3.2.2 Performance Properties Tested

Properties tested were based on the following criteria:

1. Property is considered to be critical for coating performance.
2. Property was indicated by BMS to be met with the formulation tested. (Example: The formulation had not yet been color matched to current USAF coatings.)
3. Property was considered indicative of the coatings performance in similar tests. (Example: There are multiple fluid resistance tests in the JTP; only three were utilized in this test.)

Table 27 shows the tests conducted.

Table 27. Tests Conducted

Test	ASTM	Requirement	Panels
Surface Appearance	None	No defects	All
Crosshatch Adhesion	D3359B	4B or 5B	Topcoat and Primer – Min (3) Topcoat and Primer – Opt (3)
Wet Tape Adhesion	D3359A	4A or 5A	Topcoat and Primer – Min (3) Topcoat and Primer – Opt (3)
Pencil Hardness	D3363	HB or harder	Topcoat and Primer – Min (3) Topcoat and Primer – Opt (3)
GE Impact	D6905	40% flexibility	Flexibility Specimen – Min (3) Flexibility Specimen – Opt (3)
Humidity Resistance	D2247	No blistering, softening, adhesion loss	Topcoat and Primer – Min (3) Topcoat and Primer – Opt (3)
Heat Resistance of 250 ± 5 °F for 60 minutes	Method 6051	Color change (ΔE) of $\leq$ 1	Topcoat and Primer – Min (3) Topcoat and Primer – Opt (3)
Accelerated Weathering – 500 Hours	G155	Color change (ΔE) of $\leq$ 1; 60 °gloss change $\leq$ 1	Topcoat and Primer – Min (3) Topcoat and Primer – Opt (3)
Fluid Resistance			
Lube Oil	None	Softening $\leq$ 2 pencil hardness units	Topcoat and Primer – Min (3) Topcoat and Primer – Opt (3)
JP-8 Jet Fuel	None	Softening $\leq$ 2 pencil hardness units	Topcoat and Primer – Min (3) Topcoat and Primer – Opt (3)
30 Days Deionized Water	None	Softening $\leq$ 2 pencil hardness units	Topcoat and Primer – Min (3) Topcoat and Primer – Opt (3)

6.3.2.3 Test Data

6.3.2.3.1 Surface Appearance

The surface appearance of all panels was up to acceptable standards on visual inspection. The coating achieved complete coverage of the primer, and the surface was smooth and unmarred.

Figure 18 shows a selection of the gloss white specimens from various tests.

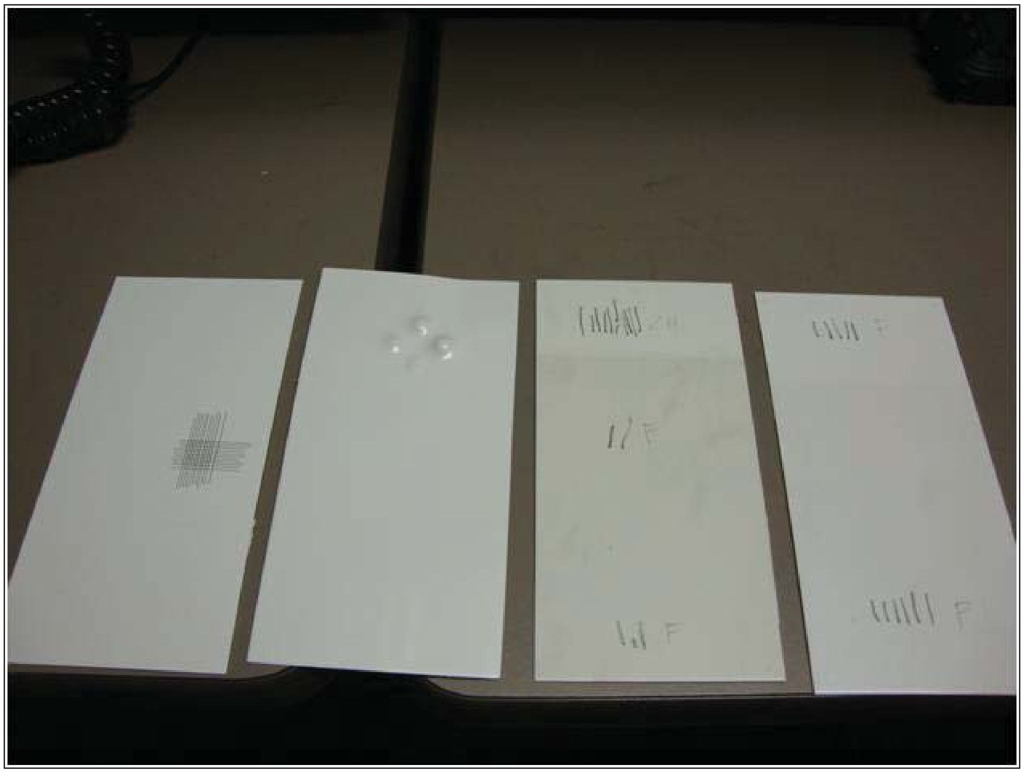


Figure 18. CTC Screened Gloss White Specimens

In order they are: crosshatch adhesion specimen (far left), GE impact flexibility specimen (middle left), lube oil fluid resistance specimen (middle right), and JP-8 jet fuel fluid resistance specimen (far right).

6.3.2.3.2 Crosshatch Adhesion

The requirement for wet tape adhesion is a result of 4B or 5B when tested according to D3359B. The crosshatch adhesion test results are shown in Table 28.

Table 28. Crosshatch Adhesion Results

Sample ID	Cure Intensity	Results
2938	Minimum	5B
2939	Optimum	5B
2940	Optimum	5B
2941	Minimum	5B
2942	Minimum	5B
2943	Optimum	5B

Analysis: The gloss white samples met requirements for crosshatch adhesion on both minimum and optimum cure panels.

6.3.2.3.3 Wet Tape Adhesion

The requirement for wet tape adhesion is a result of 4A or 5A when tested according to D3359A. The wet tape adhesion test results are shown in Table 29.

Table 29. Wet Tape Adhesion Results

Sample ID	Cure Intensity	Results
2944	Optimum	4A
2945	Minimum	4A
2946	Minimum	4A
2947	Optimum	4A
2948	Optimum	1A*
2949	Minimum	4A

*Most coating removed from scribe area

Analysis: The gloss white samples met requirements for wet tape adhesion for five out of six samples. The remaining sample was from an optimum cure specimen and may have been an outlier due to defect or faulty surface preparation.

6.3.2.3.4 Pencil Hardness

Though there is no specific performance specification for baseline pencil hardness, stakeholders have indicated that a minimum pencil hardness of HB is desirable for aerospace coatings. The pencil hardness test results are shown in Table 30. Two tests were performed on each panel.

Table 30. Pencil Hardness Results

Sample ID	Cure Intensity	Result 1	Result 2
2956	Optimum	F	HB
2957	Minimum	B	B
2958	Minimum	HB	HB
2959	Optimum	HB	HB
2960	Optimum	F	HB
2961	Minimum	HB	HB

Analysis: The gloss white samples met the HB minimum pencil hardness for 5 out of the 6 specimens. The remaining specimen, 2957, falls one pencil hardness unit below the desired minimum of HB. Per past experience with UV-curable topcoats, pencil hardness is considered to be one of the primary indicators of state of cure. Potentially a full cure ladder study would indicate that coating under the minimum exposure area requires a greater exposure time to achieve complete cure.

6.3.2.3.5 GE Impact Flexibility

The requirement for GE Impact flexibility is to withstand a minimum of 40% elongation without surface cracking when tested using a GE Impact-Flexibility Tester and examined under ten-power magnification. The GE Impact flexibility test results are shown in Table 31.

Table 31. GE Impact Flexibility Results

Sample ID	Cure Intensity	Results
3004	Optimum	40%
3005	Minimum	40%
3006	Minimum	40%
3007	Optimum	40%
3008	Optimum	40%
3009	Minimum	40%

Analysis: The gloss white samples met requirements for GE Impact flexibility on all coating samples.

6.3.2.3.6 Humidity Resistance

The requirement for humidity resistance is to withstand exposure for no less than 30 days in a humidity cabinet maintained at 49 ±2 °C (120 ±3 °F) and 100 percent relative humidity (RH) without blistering, softening, exhibiting any loss of adhesion, nor other film defects. The humidity resistance test results are shown in Table 32.

Table 32. Humidity Resistance Results

Sample ID	Cure Intensity	Specimen Appearance
2986	Minimum	Failed; blisters observed at 14 day mark
2987	Optimum	Failed; blisters observed at 14 day mark
2988	Optimum	Failed; blisters observed at 14 day mark
2989	Minimum	Failed; blisters observed at 14 day mark
2990	Minimum	Failed; blisters observed at 14 day mark
2991	Optimum	Failed; blisters observed at 14 day mark

Analysis: The gloss white samples showed signs of blistering at 14 days into the 30 days evaluation period. These results were communicated back to BMS to be addressed in the final coating formulation. Pictures of two representative samples are shown in Figures 19 and 20 below.

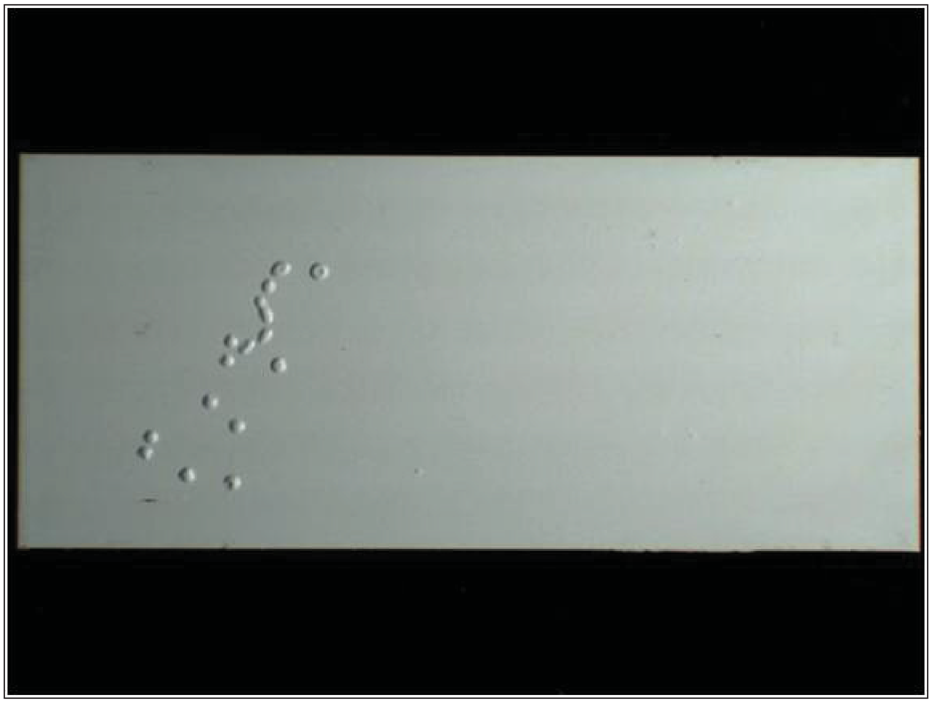


Figure 19. Humidity Resistance Sample 2990

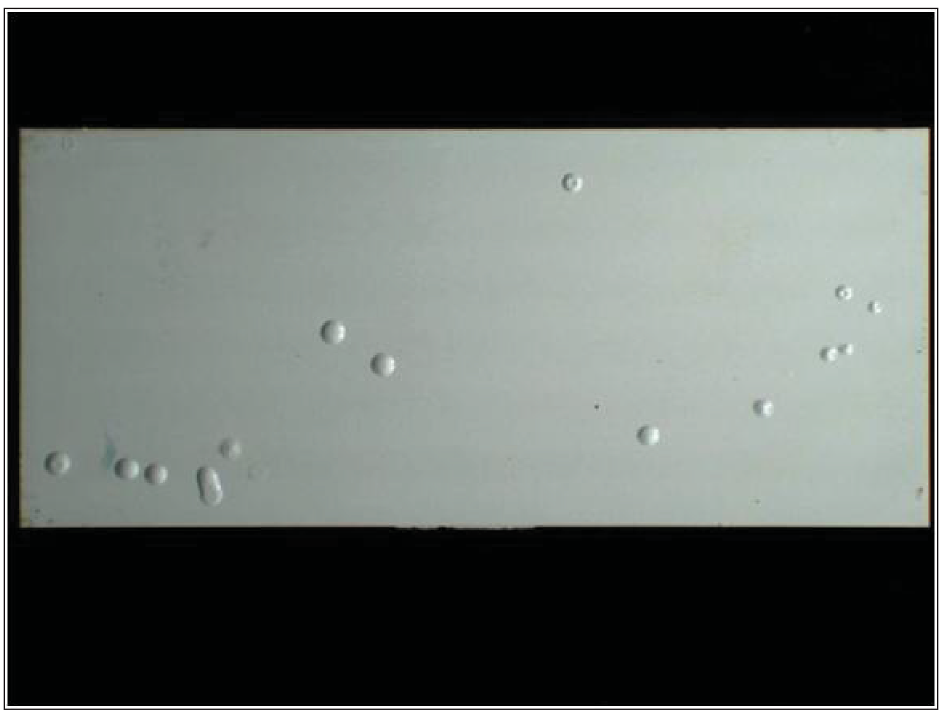


Figure 20. Humidity Resistance Sample 2987

6.3.2.3.7 Heat Resistance

The minimum requirement for heat resistance is to withstand 121 ±3 °C (250 ±5 °F) for no less than 60 minutes, in accordance with FED-STD-141, method 6051, and to show a color change (ΔE) of ≤ 1. The heat resistance test results are shown in Table 33.

Table 33. GE Heat Resistance Results

Sample ID	Cure Intensity	ΔE
2980	Optimum	1.40
2981	Minimum	1.25
2982	Optimum	1.25
2983	Optimum	1.25
2984	Minimum	0.94
2985	Minimum	1.01

Analysis: The gloss white samples were overall failures for heat resistance. However the degree of failure was low.

6.3.2.3.8 Accelerated Weathering

The minimum requirement for accelerated weathering resistance is that after 500 hours in a xenon arc chamber, the coating will show a color change (ΔE) of ≤ 1 and have a gloss of 80 or higher. Due to limited availability of the accelerated weathering chamber, there was no opportunity to begin weathering testing until over a month after application of the samples. Due to the additional formulation work that was conducted during this time, it was concluded that there was limited utility in proceeding with weathering resistance testing on samples that would require reformulation due to other tests.

6.3.2.3.9 Fluid Resistance – Lube Oil

The minimum requirement for lube oil resistance is that after 24 hours exposure to lube oil conforming to MIL-L-23699 at 121 ±3 °C (250 ±5 °F), the coating shall not exhibit any blistering, softening more than 2 pencil hardness units, or other coating defects. Slight staining of the coating is acceptable. The lube test results are shown in Table 34.

Table 34. 24 Hour Lube Oil Results

		Pre-Immersion		Post-Immersion		
Sample ID	Cure Intensity	Gloss	PH	ΔE	Gloss	PH
2962	Minimum	61.67	2H	6.33	34.33	F
2963	Optimum	68.23	2H	6.25	43.40	F
2964	Optimum	68.27	2H	6.31	41.67	F
2965	Minimum	67.37	2H	6.11	39.63	F
2966	Minimum	72.30	2H	6.15	40.17	F
2967	Optimum	73.77	2H	6.53	41.57	F

Analysis: The gloss white samples showed softening within the allowable parameters and some minor staining after 24-hour lube oil exposure.

6.3.2.3.10 Fluid Resistance – JP-8 Jet Fuel

The minimum requirement for jet fuel resistance is that after 7-days exposure to jet fuel conforming to MIL-DTL-5624 at room temperature, the coating shall not exhibit any blistering, softening more than 2 pencil hardness units, or other coating defects. Slight staining of the coating is acceptable. The jet fuel results are shown in Table 35.

Table 35. Jet Fuel Results

		Pre-Immersion		Post-Immersion		
Sample ID	Cure Intensity	Gloss	PH	ΔE	Gloss	PH
2968	Optimum	73.57	F	1.31	68.97	F
2969	Minimum	71.23	F	1.26	68.03	B
2970	Minimum	65.80	F	1.12	60.53	HB
2971	Optimum	69.80	F	2.36	67.13	F
2972	Optimum	72.03	F	2.13	70.03	HB
2973	Minimum	71.40	F	2.18	69.23	HB

Analysis: The gloss white samples showed softening within the allowable parameters and no significant staining after 7 day jet fuel exposure.

6.3.2.3.11 Fluid Resistance – 30 Day Deionized Water

The optimum criteria requirement for deionized water resistance is that after 30 days, the coating shall not exhibit any blistering, softening more than 2 pencil hardness units, or other coating defects. Slight staining of the coating is acceptable. The water results are shown in Table 36.

Table 36. 30 Day Water Results

Sample ID	Cure	Gloss

	Intensity	
2986	Minimum	Failed, Blisters
2987	Optimum	Failed, Blisters
2988	Optimum	Failed, Blisters
2989	Minimum	Failed, Blisters
2990	Minimum	Failed, Blisters
2991	Optimum	Failed, Blisters

Analysis: All samples failed water resistance, confirming conclusions that the humidity resistance performance of the NB# 986095 required improvement.

6.3.2.4 Overall Analysis

The NB# 986095 coating failed when exposed to water, and was at the lower end of the desired range of pencil hardness. These results were communicated back to the BMS/Deft team for coating rework.

6.3.3 Final BMS/Deft Gloss White Performance Testing

The BMS/Deft partnership continued development work over the following months attempting to address several major performance issues. These were primarily attempts to meet the 90 at 60° gloss requirement, introducing sag resistance in the coating while making it sprayable, and improving humidity resistance properties.

August 2010 Progress

BMS/Deft accomplished the following in August:

- Tested thixotrope additives to reduce sag resistance.
- Tested gloss-increasing additives, but could not achieve above 83.
- Weathering results on NB# 986095 was completed. Results are shown in Table 37.

Table 37. Weathering Results on NB# 986095

Number of Hours	60° Gloss	ΔE
0	75	---
500	68	0.66
1000	63	0.70
1500	57	0.76
2000	56	0.70

- Optimized pigment loading
- Evaluated flow / leveling additives

- Evaluated three reactive diluents

September 2010 Progress

BMS/Deft accomplished the following in September:

- Identified thickeners and thixotrope to improve for sag resistance. Tested them in various combinations to determine effect on surface appearance. The thixotropes seemed to work better than thickeners.
- Evaluated freeze/thaw stability by freezing samples at -9°C for 18 hrs. Out of 7 coating formulations evaluated, 5 out of 7 failed at one cycle.

October/November 2010 Progress

- BMS/Deft determined that coating could be made to pass humidity resistance testing if allowed a 7-day post-cure and if appropriate primer was used. Formulations used with non-Deft qualified primer or not allowed post-cure continued to fail humidity testing.
- In addition, attempts to raise the gloss value to the 90 at 60° requirement continued to fail. On December 1, 2010, BMS sent formal communication stating, "Our current best formulation has issues meeting the gloss requirement of the JTP and we do not expect the Deft's reformulation efforts to be able to meet this requirement."

6.3.4 Risk Assessment and Decision

Based on Deft's reported results, a risk assessment table was created and shared with stakeholders from the USAF, USCG, and USN. This assessment is shown as Table 38.

Table 38. Gloss White Risk Assessment Table

Property	Risk Coatings Will Not Meet Requirement
Color	Low Risk
Gloss	High Risk
Wet Tape	Low Risk
Cross Hatch	Low Risk
MEK Rub	Low Risk
Stencil Coat Adhesion	Some Risk (untested)
Low Temp Flex	Low Risk
GE Impact	Low Risk
Pencil Hardness	Some Risk
Fluid Resistance	Some Risk
Accelerated Weathering	Some Risk
Heat Resistance	High Risk
Humidity Resistance	High Risk
Cleanability	Some Risk (untested)
Salt Spray	Some Risk (untested)
Strippability	Some Risk(untested)
Repairability	Some Risk (untested)

A roundtable teleconference was held with stakeholders from the USAF, USN, and USCG on December 20, 2010, to determine if moving forward with the gloss white was justified given the strong likelihood that all performance requirements would not be met. One of the major factors in the decision was the degree to which the gloss requirement was being failed. Maintaining professional military appearance is a major function of DoD aerospace topcoats, and a coating that could not match required high-gloss appearance would not be acceptable. While an exception to the mil-spec might potentially have been made if the coating only missed the gloss requirement by a few units, the formulations tested achieved gloss of around 80 units at most, with the requirement being 90. In addition, during accelerated weathering testing the formulations regularly lost 10 or more units of gloss, making the change in appearance extremely visible. Based on stakeholder input, further attempts to optimize and implement the BMS/Deft gloss white were discontinued.

6.4 CTC/BBM Technologies Flexible Flat Coatings

6.4.1 CTC/BBM Coating Approach

With the discontinuance of further optimization/implementation efforts for both flat and gloss BMS/Deft coatings, the project was left without a viable UV-curable coating to utilize in a field demonstration or attempt to implement. However, the experience gained with UV-curable coating development through the course of the project offered a potential solution. This solution was to make an open-ended survey of commercially available UV-cure resins that could serve as the basis for an aerospace coating. Unlike with the BMS/Deft efforts, this survey would not be limited to resins manufactured by Bayer Material Science but would also include resins produced by other major resin manufacturers such as Cytec and Sartomer.

In BBM's experience in formulating aerospace coatings, one of the toughest MIL-PRF-85285 requirements to meet is GE Impact flexibility. A huge premium is placed upon flexibility due to the degree which the aircraft structure may bend during flight. Based on the feedback provided during the Deft/Bayer efforts as well as data from the 2008 screening testing, flexibility was a major problem area for promising UV-curable coatings. A traditional drawback to UV technology is the extremely brittle nature of the final film. Manufacturers attempted to focus on other performance properties and only address flexibility near the end of the development process.

When CTC and BBM Technologies undertook a new coating effort as detailed in Section 5.1.4, the effort focused upon identifying extremely elastomeric resins which could meet GE Impact elongation requirement of 40% or more while still being tough enough to provide resistance in fluid and humidity tests. By focusing on a high flexibility from the beginning, sufficient latitude was allowed to "build" a high surface hardness as the effort progressed into Phase 2 as fillers and pigments were added. Extreme crosslink density, which yields high chemical resistance and surface hardness, severely limits the overall thickness of the film and properties like impact resistance and flexibility.

At the same time, the effort addressed the unique challenges due to the "low energy" UVA cure that is required. Photoinitiators were selected based on the emission spectra of the H&S Autoshot Cure-Tek lamp system. Due to the nature of curing pigmented systems, photoinitiators had to be selected that absorb in a different area of the spectrum than do the pigments.

6.4.2 Resin Evaluation

Resin screening occurred from January 31 through May 5, 2011. The evaluation was conducted on various clear coat blends of UV resins and photoinitiators obtained as samples from major manufacturers. These samples were chosen according to vendor recommendations based on the properties that were targeted. Resin suppliers contacted included Bayer, Cytec, Rahn, and Sartomer. Photoinitiator suppliers contacted were BASF, Cytec, and Rahn. 42 resins and 10 photoinitiators were evaluated in 140 system combinations.

The UV resins investigated were the following types:

- **Urethane Acrylates:** Urethane Acrylates are the most versatile UV curing resins. Their backbone can impart a blend of hardness/flexibility to the final formulation.
- **Epoxy Acrylates**: Tend towards higher hardness and lower elongation. Generally are diluted with mono- or difunctional acrylates (reactive diluents) in order to overcome viscosity concerns.

- **Polyester Acrylates:** Improve UV reactivity. Can impart good surface properties such as mar resistance and high crosslink density.
- **Reactive Diluents**: These acrylates can be a subset of the other classes. They are low functionality (1, 2 or 3) that aid in adjusting the overall viscosity of the resin system without the addition of solvents thereby keeping VOCs to a minimum. They also can be used as adhesion promoters and help to zero in on specific properties that the resin system may benefit from.

The photoinitiators utilized fit the following types:

- **Homolytic Fragmentation Type**: Produce two free radicals when activated by UV radiation. Main absorption range falls in the low end of UVA radiation 320-340nm. Also has a strong absorption in UVB range (useful for full spectrum curing)
- **Hydrogen Abstraction Type:** Used in combination with amine synergists. These are active in a wider range of the UVA spectra 320-385 nm. The synergists can be incorporated into the final film and enhance properties.

All resins were screened individually in order to baseline their hardness, flexibility, solvent resistance and overall cure response. Based upon these results, resins were downselected into “high elongation” and “high pencil hardness” categories. These systems where then blended in a ladder study in order to optimize the resin systems’ properties as laid out in the success criteria. It should be noted that additives were not included. The solvent used was t-Butyl-Acetate, which provided good solubility for the resins, which were thick and viscous out of the bottle.

The success criteria were that the resin fully cure when exposed to light produced by the Cure-Tek 1200 in the 320-400 nm wavelength range and be able to do so in all thicknesses in the 1.7-3.5 mil range. After observation of depot paint processes, 3.5 mils or less was deemed to be the thickness range that a trained painter could reliably spray with HVLP equipment in an operational environment. The performance criteria were:

- 40%+ GE Impact flexibility
- Pass low-temperature mandrel bend
- Adhesion of 4A/4B or better to MIL-PRF-23377 primer
- Pencil hardness 2H or greater
- 100 MEK double-rub resistance
- Pass fluid resistance as per MIL-PRF-85285 when subjected to the following fluids: lube oil, hydraulic fluid, jp-8 fuel and water

At the conclusion of testing, five resin blends were chosen for advancement to be tested as pigmented coatings. The best candidates were those that displayed the highest overall pencil hardness while maintaining the ability to pass low temperature mandrel bend flexibility. In addition to this selection, precedence was given to systems that displayed the fastest cure time. Table 39 shows the five resin blends.

Table 39. Resin Blends Passing to Pigmented Testing

System	Adhesion	PH	GE Impact	Mandrel Bend	MEK Rub	Lube Oil	Hydraulic	JP-8	Water
Requirement	**4A/4B**	**2H+**	**>40%**	**Pass**	**>100**	**</2 units PH loss**	**</2 units PH loss**	**</2 units PH loss**	**</2 units PH loss**
Cytec 8411/Bayer U400	5A/5B	2H	>40%	Pass	>100	2H/2H	2H/H	2H/H	2H/2H
Cytec 8807	5A/5B	3H	>40%	Pass	>100	3H/H	3H/H	3H/H	3H/3H
Cytec 8804	4A/4B	2H	>40%	Pass	>100	2H/2H	2H/2H	2H/H	2H/2H
Cytec 4833	5A/5B	3H	>40%	Pass	>100	3H/3H	3H/3H	3H/3H	3H/3H
Sartomer CN996	4A/4B	H*	>40%	Pass	>100	H/H	H/F	H/H	H/H

* Although the success criterion was 2H+ pencil hardness, a decision was made to pursue Sartomer CN996 due to knowledge that addition of fillers and pigments would increase hardness and decrease flexibility. A lower-hardness option provided a safety net if increasing hardness resulted in decreasing flexibility.

Full detail on all 140 resin blends evaluated can be found in Appendix H, Resin Screening Data. The resins chosen were all di-acrylates (two link points) for the flexibility they provide over the three-point linkages. Candidates were limited out of the numerous resin packages available, as flexibility is not commonly sought to the degree that the USAF needs it in aerospace coatings.

6.4.3 Creation/Testing of CTC/BBM Pigmented Coatings

From May 2011 through February 2012, the selected resins were formulated into pigmented coatings. This included selection of pigments and flattening agents to meet the color and gloss requirements, selection of additives to provide resistance to weathering, adhesion improvements, surface modifiers, and final solvent blend. The final formulations were then tested against key performance requirements.

6.4.3.1 Pigments and Flattening Agents

Pigment selection was carried out by looking at commercially available white and black pigments. Because the target colors were black and grays, both white and black pigments were required. Priority was given to pigments carried by major suppliers to ensure continued availability of supply if the coatings were implemented. Table 40 shows the results. “DNT” indicates “did not test” as the coating did not achieve proper cure.

Table 40. Pigment Testing Results

Material	Color	Pigment Binder Ratio	Pigment Volume Concen-tration (%)	Vehicle	MEK Rubs	PH	Elongation
Dupont TiO2 R-960	White	0.44	11.3	Cytec 4833	50	3H	40%
Millenium Tiona RCL-3	White	0.39	10.1		50	H-2H	40%
Kronos TiO2 2160	White	0.39	9.8		50	H	40%
Huntsman Tioxide TR93	White	0.39	9.9		50	2H	40%
Kemira TiO2 RD3	White	0.39	9.7		50	2H	40%
Ferro V-10201 Eclipse	Black	0.2	3.06		50	3H	40%
Raven 450	Black	0.2	11.21		DNT	DNT	DNT
		0.1	5.94		DNT	DNT	DNT
		0.02	1.3		50	3H	40%
Lansco CB 490-P	Black	0.2	10.93		DNT	DNT	DNT
		0.1	5.78		DNT	DNT	DNT
		0.04	2.2		50	3H	40%
Shepherd 10L927	Black	0.2	3.87		50	3H	40%
Monarch 1500	Black	0.06	4		50	3H	40%
Ferro F-6331	Black	0.2	3.3		50	HB	40%
Bayferrox 318M	Black	0.2	4.6		50	HB	40%
Raven 5000 Ultra III	Black	0.05	3.3		50	HB	40%
Dupont TiO2 R-960	White	0.44	10.8	Cytec 8807	50	H	40%
Millenium Tiona RCL-3	White	0.39	9.7		50	F	40%
Kronos TiO2 2160	White	0.39	9.38		50	HB	40%
Huntsman Tioxide TR93	White	0.39	9.52		50	H	40%
Kemira TiO2 RD3	White	0.39	9.27		50	H	40%
Ferro V-10201 Eclipse	Black	0.2	2.9		50	H	40%
Raven 450	Black	0.1	5.7		DNT	DNT	DNT
		0.02	1.3		50	H	40%
Lansco CB 490-P	Black	0.1	5.5		DNT	H	40%
		0.04	2.1		50	H	40%
Shepherd 10L927	Black	0.2	3.7		50	H	40%
Monarch 1500	Black	0.06	3.8		50	H	40%
Ferro F-6331	Black	0.2	3.1		DNT	DNT	DNT
Bayferrox 318M	Black	0.2	4.4		DNT	DNT	DNT
Raven 5000 Ultra III	Black	0.05	3.2		DNT	DNT	DNT

The most important determination was that a pigment volume concentration of 5% or less was required or the system would not cure. A surface cure could be achieved, but it would not cure below 2 to 3 mils. At this point gloss white pigments seemed to reliably yield a high gloss, with gloss values above 90 in a basic coating without additives. All the white pigments performed relatively equally, and Dupont R-960 was selected due to high reliability in supply. The black pigment, the Ferro 10201 Black, was chosen based on the properties at the time (flexibility and hardness and fluid resistance and MEK resistance).

An extensive study was conducted on gloss reduction agents. Achieving the 85° gloss requirement of 9 or less presented a severe problem as compared to the 60° gloss requirement of 5 or less. Table 41 shows the results.

Table 41. Pigment Survey

Number	Material	Loading (g)	Loading (%) TW	Cure Time	60° Gloss	85° Gloss	PH	Control #
1	Blanc Fixe	7.5	13	8 minutes	30.7	59	<HB	1
2	Syloid 7000	3.5	6.6	8 minutes	14.5	48	F-H	1
3	Fluo 300XF	7.5	13	8 minutes	17.8	64	<HB	1
4	**AceMatt HK450**	3.5	6.6	8 minutes	6	3.4	>2H	1
5	Micropro 600VF	7.5	13	8 minutes	44.3	67	<HB	1
6	Nytal 7700	7.5	13	8 minutes	49.1	78	H-2H	1
7	MP Fluo HTLS	7.5	13	8 minutes	14.1	71	F-H	1
8	Propylmatte 31	7.5	13	8 minutes	44.5	60	HB	1
9	**AceMatt 3300**	3.5	6.6	8 minutes	2.3	13	2H	1
10	Propyltex 270S 1518	7.5	13	8 minutes	48	61	F	1
11	Vansil W-30	7.5	13	8 minutes	51	80	>2H	1
12	Imsil A-10	7.5	13	8 minutes	33	68		1
13	**AceMatt HK440**	3.75	7	8 minutes	3.8	21.5	>2H	1
14	AceMatt OK412	3.75	7	8 minutes	37	77	>2H	1
15	**AceMatt TS100**	3.75	7	8 minutes	0.4	0.3	HB	1
16	PPG Lo-Vel 2003	3.75	7	8 minutes	24.5	54	>2H	1
17	**Lubrizol Matt 2000**	7.5	13	8 minutes	1.5	12.6	>2H	1
18	Syloid C906	3.75	7	8 minutes	15	46	>2H	1
19	Nylotex 200	7.5	13	8 minutes	41	46.6	H	1
20	MPP-620XF	7.5	13	8 minutes	16.9	42.3	F	1

Table 41. Pigment Survey (Continued)

Number	Material	Loading (g)	Loading (%) TW	Cure Time	60° Gloss	85° Gloss	PH	Control #
21	Synfluo 180VF	7.5	13	8 minutes	20.4	52.6	F	1
22	MicroMatte 1214 UVW	7.5	13	8 minutes	31.5	82.9	<HB	1
23	Shamrock TexMatte 6017	7.5	13	8 minutes	68.2	81.7	>2H	1
24	OptiWhite MX	7.5	13	8 minutes	34.3	87.7	>2H	1
25	Kynar	7.5	13	8 minutes	16.8	25		2
Control 1	Pigmented Coating w/ no Flattener	N/A	N/A	8 minutes	63.2	81.4	H-2H	1
Control 2*	Pigmented Coating w/ no Flattener			8 minutes	80.6	91		2

* Ran out of control 1

The Acematt and Lubrizaol Matt products, which are silica-based, were selected for moving forward in combination with glass bubble additives.

Lessons Learned

If future development work were conducted, there are many materials that can serve as a flattening agent. As an example, one UV version contains some acrylate functionality that was not used because it takes away flexibility. The main concern with flattener usage is that the amounts required to achieve the required gloss degrade performance properties. It might be desirable to make gloss more of a priority from the beginning and use an additive to create a gloss reducing binder system from the ground up. By encapsulating a material in something hazy, it would be possible to reduce the need for additive materials. This would decrease the porosity of the film, allowing better fluid resistance and flexibility by avoiding particles of pigments rubbing up against each other.

Pigments and flatteners should be investigated simultaneously. It is necessary to get the flattening agents into the glossy pigment-only coatings before looking at any other properties.

6.4.3.2 Weathering Resistance Additives

Because the MIL-PRF-85285 accelerated weathering test requires 500 hours to conduct, it was necessary to use a faster test to obtain results. This was done with a harsh UVB-based test that utilized UVB light at 313nm. The test method was based on a test used in the automotive industry, #3 QUV Cycle E: Method ASTM G154 Cycle 5. The irradiance was UV 0.62 W/m^2 irradiance with a 24-hour cycle of temperature of 80°C for 20 hours followed by condensation at

50°C for 4 hours. Screening was conducted for 168 hours, allowing each testing cycle to be completed in one week,

The weathering packages chosen for testing were based on the packages that went into current MIL-PRF-85285 Type IV systems. Five weathering packages were screened with four resins under consideration. The weathering packages were all combinations of UV-absorbers, light stabilizers, and anti-oxidants. The testing was conducted on coatings using a gray 36173 pigment package. The results are shown in Table 42.

Table 42. UVB Weathering Tests

System	Package #1	Package #2	Package #3	Package #4	Package #5
MIL-PRF-85285 Control	0.83746	0.83746	0.83746	1.006991	1.006991
Cytec 8804	0.870394	0.768335	Fail	Fail	Fail
Cytec 8807	Fail	0.458018	0.902413	Fail	Fail
Cytec 4833	Fail	Fail	0.629826	0.870991	0.496261
Sartomer CN996	Fail	Fail	0.839646	Fail	Fail

Readings are delta-E values from pre-exposure

Three of the packages seemed to perform acceptably in the UVB chamber. New samples were created for these three packages and they were retested. In the end, a weathering package based on a combination produced by Mayzo was selected. This was partially resin dependent, as the package when placed in a blend of Ebecryl 4833 and 4811 produced the best properties of 0.5 delta E in this resin/weathering package combo as compared to 0.9 in the others. There was another package in a different resin that had as good a weathering but seemed less robust in the other properties.

6.4.3.3 Other Properties

Adhesion

Adhesion became a problem at various points in the development cycle. The base resin systems adhered to primer, but as pigments and flattening agents were added the wet tape adhesion started to break down and fail requirements. Ladder studies were conducted with UV monomers known to improve adhesion. Monomers were added at 1%, 5%, 10%, and 15% which also created improvement in other properties. However as adhesion improved it had a negative impact on flexibility due to becoming too crosslinked. Films were harder and more resistant but cracked when tested with GE Impact and mandrel bend. Ultimately a 1,6-Hexanediol diacrylate monomer was used as an adhesion promoter at a minimal 5% level, sufficient to give 4A adhesion or better.

Adhesion properties and monomer additives were looked at throughout the project, with tweaks and changes made all the way until the very end. Other factors such as panel preparation or length of time since primer was applied could also affect adhesion, making it a difficult property to study.

Surface Modifiers
"Surface modifiers" was a small category of changes with criteria largely subjective. Evaluation was based on if the paint seemed to be flowing out better and having a superior appearance. However, a slicker surface modifier can have an effect on tests such as pencil hardness. Things to tighten up the surface were also useful to try to avoid blisters from humidity exposure. Several surface modifier agents were evaluated, and Byk UV 3500 was selected in the end.

Solvents
As VOC reduction was an environmental goal of this project, the direction was to utilize only exempt solvents. A three solvent combination was settled on. Acetone was used a fast-evaporating solvent, t-butyl-acetate as a medium-evaporating solvent, and oxol-100 as a slow-evaporating solvent. The acetone was used mainly as a viscosity reducer in the can to make it easier to mix and easier to spray. The oxsol and t-butyll acetate do the flow-out and rheology work on the panel. Once a solvent package was settled on early in the effort, it was not varied.

Lessons Learned
In a future effort, it would be recommended to spend more time looking at monomers to try and reduce the solvent content.

6.4.3.4 Requirements Testing

Once a final formulation had been settled on, the 36173 gray and 37038 black were evaluated for their ability to meet major performance requirements prior to entering formal JTP testing. The 36118 gray would be color matched based on the 36173 gray if it successfully completed testing. This testing was completed as of December 22, 2011. The results for the 36173 gray are shown in Table 43.

Table 43. Interim Key Performance Requirements

Tests	Target Criteria	Performance of UV-Curable 36173 Gray
Color[1]	Color difference (ΔE) of less than 1 from FED-STD-595	Pass
Gloss	At 60° ≤5; ≤9 at 85°	Pass (1.1 at 60° and 7.2 at 85°)
Drying Time	Set to touch within 6 hours and dry-hard within 12 hours	Pass (3 mil thick coating cured in 12 minutes with UV-A lamp)
Wet Tape	No peel away; target rating of 4A or 5A	Pass (4A)
MEK Rub	25 double-rub no substrate exposure	Pass
Low Temperature Flexibility	No cracking or adhesion loss over 2 inch bend at (-60 °F)	Pass
GE Impact	Minimum of 40% elongation; no cracking, adhesion loss	Pass
Lube oil resistance	No defects; softening <2 PH after 24 hrs at 250 °F	Pass
Hydraulic fluid resistance	No defects; softening <2 PH after 24 hrs at 150 °F	Pass
JP-5 Fuel Resistance	No defects; softening <2 PH after 7 days at room temperature	Pass
Accelerated Weathering (Color and Gloss)	Color change (ΔE) of less than 1 after 500 hours; Maximum five (5) gloss @ 60°	Pass (ΔE of 0.63 and Gloss <5)
Heat Resistance	Color ΔE < 1 after exposure to 250 ± 5ºF for 60 minutes	Pass (ΔE of 0.58)
Opacity[2]	Contrast ratio no less than 0.95	Pass

1. Based upon batch specific testing. Final color matching to be complete upon finalizing formulations
2. Tested over Leneta charts at spec DFT

The 37038 Black failed initial 500 hour weathering test, showing a ΔE of 3 to 5 at 500 hours. Given that the results were superior for the 36173 gray, it was assumed that the black pigment was not light stable. All the prior weathering testing had been conducted on a gray formulation. Another round of weathering using a different selection of black pigments was attempted to achieve acceptable weathering results, but the coating again failed. Since the resin packages and photoinitiators and flattening agents were all the same as with the gray coating and the amount of black pigment being the only difference, the problem must be attributed to the black pigment. At this point the black color was dropped from the CCT/BBM effort and further testing and demonstration carried forward using the gray coatings only.

6.4.4 CTC/BBM Coating JTP Testing

The laboratory formulation for the CTC/BBM UV-curable coating was scaled up to produce batch quantities. Four quarts were created each of Gray UV-Curable 36118 and Gray UV-Curable 38173. These batches were to be utilized for JTP testing and for a planned application demonstration at OO-ALC. JTP testing was conducted using these batches at CTC's laboratory in Johnstown, Pennsylvania (with the exception of the 30 day humidity resistance test, which was conducted in the corrosion laboratory at OO-ALC). A summary of the results is shown in Table 44. Full results are in Appendix I CTC/BBM UV-Curable JTP Testing Results. The testing was conducted in March 2012.

Table 44. CTC/BBM Coatings JTP Testing

Test	Target Criteria	Results	
		36173	36118
Color	Color difference (ΔE) ≥1 from FED-STD-595	Pass	Pass
Gloss	At 60° ≤5; ≤9 at 85°	Pass	Pass
Wet Tape	No peel away; target rating of 4A or 5A	4A	4A
MEK Rub	25 double-rub no substrate exposure	>100	>100
Low Temperature	No cracking or adhesion loss over 2 inch bend at (-60 °F)	Pass	Pass
GE Impact	Minimum of 40% elongation; no cracking, adhesion loss	40%	40%
Lube oil resistance	No defects; softening <2 PH after 24 hrs at 250 °F	Pass	Pass
Hydraulic fluid resistance	No defects; softening <2 PH after 24 hrs at 150 °F	Pass	Pass
JP-5 Fuel Resistance	No defects; softening <2 PH after 7 days at room temperature	Pass	Pass
Accelerated Weathering	Color change (ΔE) of less than 1 after 500 hours; Maximum five (5) gloss	Fail	Fail
Heat Resistance	Color ΔE < 1 after exposure to 250 ± 5ºF for 60 minutes	Pass	Fail
Humidity Resistance	No blistering, softening, loss of adhesion or defects after 30 days in a humidity cabinet maintained at 120 °F and 100 percent relative humidity	Pass	Pass
Cleanability	Cleaning Efficiency ≥ 75%	Pass	Pass
Stencil coat adhesion	Pass MEK Rub and No Reduction in Pencil Hardness	Pass	Pass

As seen both colors of the UV-curable coating failed 500-hour weathering testing despite the same formulation of 36173 having passed the 500-hour accelerated weathering testing during the earlier screening testing. The UV-36173 showed a color change ΔE of 2.5, and the 36118 showed a ΔE of 2.85. However the control coatings, which were Sherwin-Williams MIL-PRF-85285 Type I Class H, also failed with a ΔE of 1.4 (for 36173) and 1.35 (for the 36118).

It was suspected that the cause of the UV-curable failure was due to problems in the scale-up from small quantity laboratory production of ounces at a time to batch production of coating in quarts at a time. Coatings formulations often require some refinement and minor tweaking during such scale-ups, as simply proportionally increasing the quantities of all ingredients does not always produce the same results.

Due to the failure of the controls, weathering testing was repeated using the same UV-curable coating batch. However the control coating was shifted to MIL-PRF-85285 Type I Class H. This testing was conducted in May 2012. In this second round of testing all the control coatings passed, but the UV-curable coatings continued to fail. No further resources were available to attempt further reformulations, and no further testing or development work was performed.

6.4.5 Application Demonstration of CTC/BBM coating at OO-ALC

The field demonstrations originally called for under the Demonstration/Validation plan could not be conducted. No UV-curable topcoat had showed a high degree of confidence for successful field performance, and no resources and time were left on the project for a one year in-service evaluation period. During the ESTCP In-Progress Review meeting on April 18, 2012, the PI presented a plan to the ESTCP to conduct an application trial on out-of-service components as a way of gaining an indication of the technology's field potential. This application demonstration was conducted on June 12, 2012, at OO-ALC in the F-16 paint hanger.

6.4.5.1 Demonstration Set-Up

The Explosion-Proof UVA Cure Lamp was shipped overland in a packing crate from Johnstown, Pennsylvania to Hill AFB. One of the arm air pistons was observed to be bent on the lamp when it was uncrated at Hill AFB, as indicated by the blue arrow in Figure 21. Despite the bent piston, the arm was still maneuverable, albeit with greater effort.

Figure 21. Bent Piston on Lamp Arm

In addition, three pins placed to ride in a semi-circular slot and control movement of the lamp head were not in proper position. Upon removal from the crate, one pin was found completely unscrewed and on the floor of the crate while the other two pins were loose and not riding in their slots. Because the screws to hold the pins were in place inside the sealed lamp head, the two loose pins were unscrewed and no attempt was made to re-attach. Duct tape was used to secure the lamp head in position.

Power and air connections were available and sufficient to start-up and operate the Explosion-Proof UVA Cure Lamp. Both minor damage locations were related to the positioning mechanisms for the arm and the head. Following the initial visual inspection the lamp was plugged in and powered up according to the provided manufacturer instructions. Light intensity readings were then taken with both the Model 5.0 (UVA + B) Solarmeter and the Model PMA2100 Solar Light meters to ensure proper light operation. Both meters registered light intensity at or above the 30 mW/cm^2 intensity specified for coating cure so the demonstration proceeded as planned.

6.4.5.2 Coating Cure Demonstration

A simulated aircraft structure known as an "A-frame" was erected in the F-16 paint hanger. This is a structure commonly used at Hill AFB to test paint processes before they are attempted on an in-service aircraft. The A-frame consisted of two aluminum surfaces supported near-vertically on an A-shaped framework. Each surface was approximately 12 feet long by 4 feet in height, though the entire surface was not utilized in the demonstration due to the limited cure area of the lamp. The entire surface was primed with PPG CA 7233 MIL-PRF-23377 Type 1 epoxy primer at a DFT of 1 mil and allowed to cure approximately eight hours, which is the manufacturer-recommended period between primer spray and application of topcoat. This primer is currently used on F-16 aircraft undergoing repaint at Hill AFB.

The color number 36173 UV-cure test coating was applied to a section of the A-frame by a Hill AFB certified aircraft painter. This is shown in Figure 22.

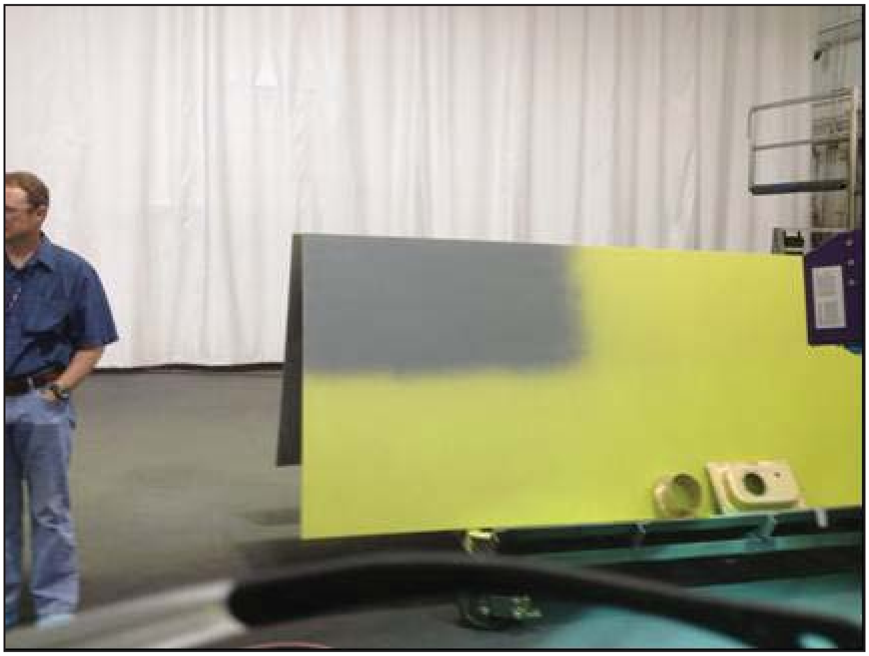


Figure 22. First Section Sprayed of CTC/BBM coating at OO-ALC

After the initial application, the wet-film thickness was measured using a standard wet-film coating thickness gauge. The initial readings showed the wet-film thickness to be 5 mils, which the applicator anticipated might produce a coating near the higher end of the intended DFT range. To ensure that coating thickness did not interfere with cure, a second section was sprayed and measured at 3.5 mil wet-film coating thickness. Both areas were allowed to flash off for 10 minutes to allow solvent to escape before the cure process began.

The lamp was then positioned to provide a curing intensity at or above 30 mW/cm^2, as measured by the UV sensors. The 5 mil wet-film thick coating area was cured for twelve minutes, and the 3.5 mil wet-film thick area was cured for ten minutes. Following cure, the section sprayed at 3.5 mil wet-film was measured at a DFT of 2 mils. Figure 23 shows the Explosion-Proof UVA Lamp being used to cure the coating sections.

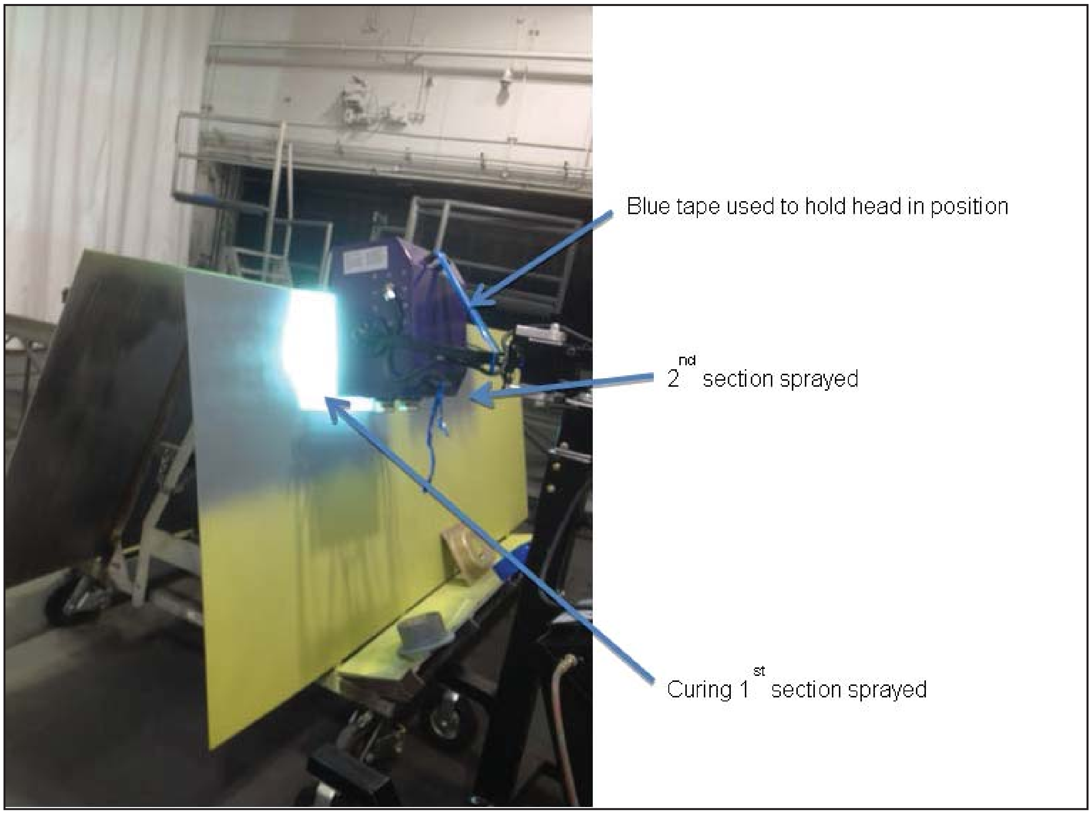


Figure 23. Cure During Field Demonstration of CTC/BBM coating at OO-ALC

The test sections were allowed to cool and were then subjected to physical tests to determine state of cure and adhesion to substrate. An MEK rub test was performed on both sections with both sections passing, indicating adequate surface cure. Tape adhesion tests were performed on each section. The tape adhesion tests consisted of applying adhesive masking tape to the coated surface, smoothing it down forcefully, and then immediately peeling away the tape. In the tape adhesion testing, both sections suffered complete failure of adhesion between the primer and topcoat. A “fingernail” test was also performed, attempting to scratch the coating off with an operator’s fingernail. Both sections also failed this test. The results of this testing on the first section are shown in Figure 24.

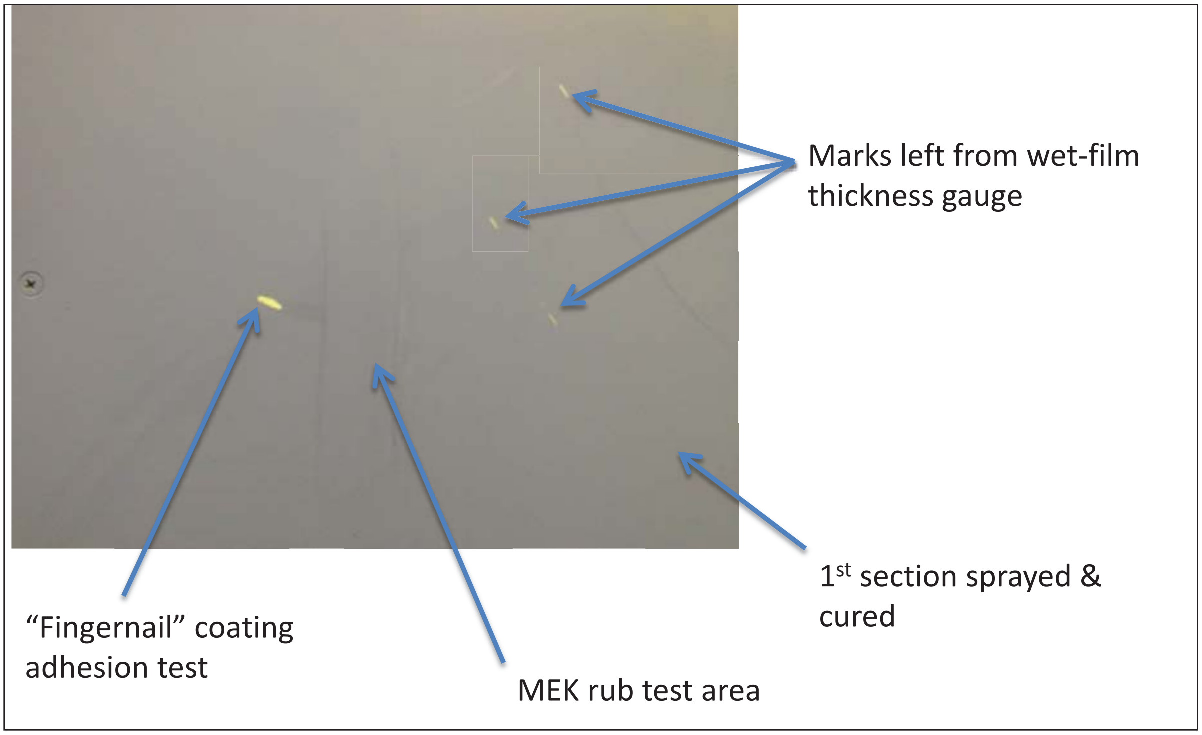


Figure 24. Cure Tests on First Section

The results of this testing on the second section are shown in Figure 25.

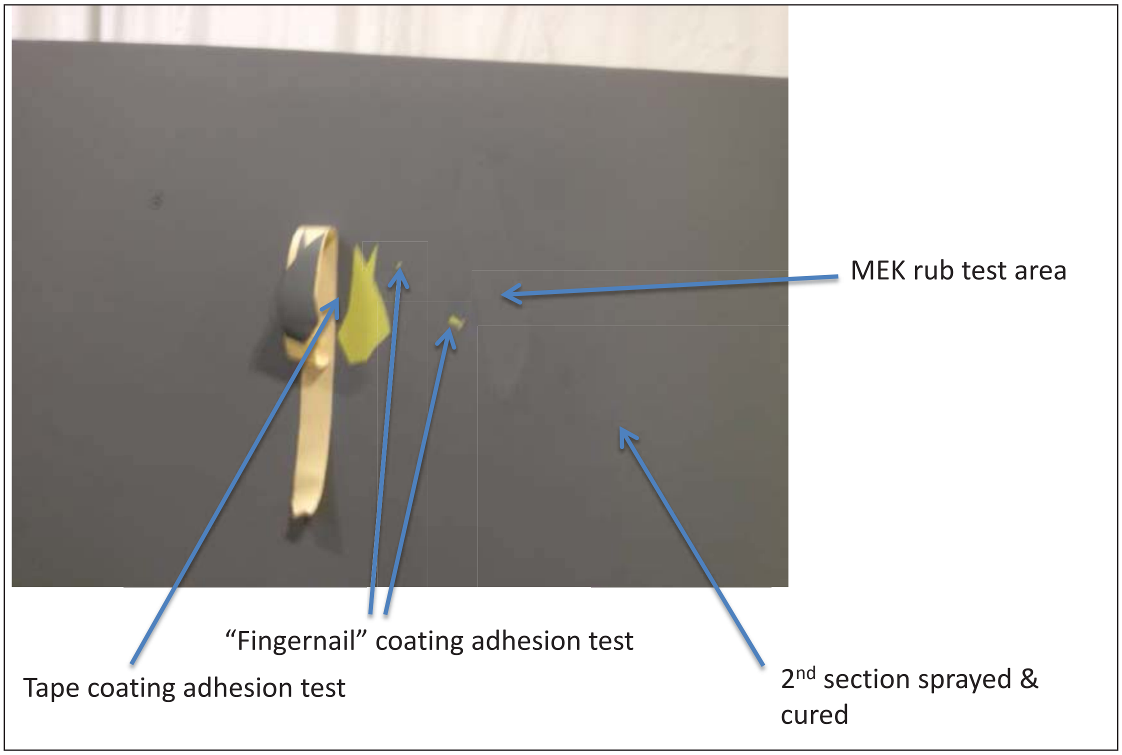


Figure 25. Cure Tests on Second Section

A pencil hardness test was attempted on the second area coated, but could not be conducted due to lack of adhesion between the primer and topcoat. Following the testing failures, the lamp intensity was measured again and was found to be at or above the recommended cure intensities. Based on the total adhesion failures of the coating, the demonstration was halted with the concurrence of the PI and no further spray/cure attempts were made with the remaining coating.

6.4.5.3 Demonstration Results Analysis

Despite minor damage to the flexible arm and head manipulation components, the Explosion-Proof UVA Lamp was successfully deployed in the field. The air and power connections were made in the F-16 paint hanger, and the UV intensity was measured to be identical to what was previously measured during controlled environment and basic functionality testing. The failure of the coating to successfully cure is attributed to problems with the coating application rather than any failure of the Explosion-Proof UVA Lamp.

This same coating batch was successfully cured during JTP testing in Johnstown, Pennsylvania using the same Explosion-Proof UVA cure lamp. The reason the coating failed to achieve successful cure at OO-ALC is unknown. However, it fits the pattern noted during this project of the successful cure UV-curable coatings being dependent on application and environment issues that do not affect the currently used coatings.

7.0 COST ASSESSMENT

7.1 Cost Model

The Initial Cost Benefit Analysis (ICBA) stated that the Environmental Cost Analysis Methodology (ECAM^{SM}) tool would be used for this effort. ECAM supports the collection and analysis of economic data in a manner that allows for more accurate evaluation of investment returns. These results are particularly helpful when evaluating pollution prevention technologies, where typical cost analysis efforts overlook second-order effects such as environmental costs. However, under this effort, no coating technology emerged that passed performance requirements or could be recommended for any DoD maintenance applications. Without a target process, no ECAM analysis could be completed.

As technological progress is made in the coatings field, new UV-curable coatings technology may emerge that is viable for DoD aircraft maintenance processes. In order support evaluations of such emerging technologies, the cost analysis section will consist of a discussion of cost factors most relevant to UV-curable coatings. Based on experience with UV coating and illumination vendors gathered during this project as well as practical experience on the requirements for implementing UV-curable coating, each relevant cost factor will be discussed in a manner that will aid future UV-curable coating technology evaluations

7.2 Cost Analysis and Comparison

7.2.1 Operating Costs

Without a final formulation or manufacturer, there is no way to know the sale price of a UV-curable aerospace coating. However, it can be hypothesized that the cost of such a coating is unlikely to be significantly less than current aerospace coatings. A UV-cure aerospace coating would have to be specifically designed for DoD aerospace requirements, meaning that there would be no economy of scale from producing it for other commercial applications. Moreover, it would initially have to be produced as a specially ordered batch coating until it was used in sufficient locations to justify continuous commercial production.

In the ICBA, one potential cost benefit was identified as the high solids nature of UV-curable coating allowing more coverage for the same coating quantity. However, subsequent UV formulation experience suggests that UV-curable coatings require a solvent content in order to be applicable by current depot paint spraying equipment, with the final CTC/BBM formulations being around 60% solid by weight. MIL-PRF-85285 has a Class H for high-solids coatings, with qualified coatings such as the Sherwin-Williams Class H being 50% to 63% solid. Consequently, there are unlikely to be any cost savings from being high solids.

Other operational costs that the current paint process requires, such as materials cost for aircraft masking and clean-up would remain under a UV-curable coatings process. Use of UV-curable coatings would incur energy costs based on the required use of UV curing lamps to cure the coatings, and a valid comparison might be made to current processes where infrared ovens are used to fast-bake coatings applied during an automated process, such as the aircraft landing gear automated line at OO-ALC.

7.2.2 Environmental Costs

Environmental drivers for this effort were based around the elimination of VOC and HAP content. However, currently used aerospace topcoats have already been steadily refined to be more environmentally friendly. Older coatings qualified to MIL-PRF-85285 such as the Defthane coating referenced in Section 3.2 do have a high HAP content, but recently formulated coatings such as the Sherwin-Williams Class H Type I have only a 0.1% by weight HAP content. In addition, the latest revision of MIL-PRF-85285 places a hard cap of 420 grams/liter or less VOC content for all qualified topcoats. If VOC elimination were to become a higher priority, it is also likely that current aerospace coatings could be reformulated to utilize only exempt solvents.

The environmental benefit of UV-curable coatings that could not be duplicated by current polyurethanes is isocyanate elimination, as isocyanates are a critical part of the cure mechanism for conventional coatings. Currently used isocyanates are not restricted, but certain individuals can develop severe sensitivities to isocyanates and this class of material may be a target for elimination in the future.

7.2.3 Labor Costs

Cost of labor was identified by OO-ALC personnel as the largest drivers of the maintenance process. However, use of UV-curable coatings provides few opportunities to reduce labor costs. Because the paint application process remains unchanged, the same labor requirement exists for application and clean-up. Labor to position and utilize curing lamps would be an additional requirement over and above current labor costs.

UV-curable coatings might reduce labor if paired with robotic painting technology, which is currently being investigated by OO-ALC and other installations as a means of reducing worker exposure to hazmats. While robotic painting could be conducted with conventional aerospace coatings, addition of UV curing lamps to the process could allow for a complete paint and cure system in which the same robot would apply and cure the coatings, greatly decreasing the total process time. This would also allow use of more intense, full spectrum UV lamps to speed the curing process and improve coating performance, as there would be no risk of worker exposure.

7.2.4 Capital Costs

The primary source of capital costs for UV-curable systems is the UV curing lamps required to achieve coating cure. Basic non-explosion-proof UVA lamps intended for automotive body shop work are relatively inexpensive, with the Cure-Tek 1200 retailing for less than $5000 United States Dollars (USD). However, these lamps provide an extremely limited cure area of around 12 inches by 12 inches (depending on the specific UV irradiance requirements of the coating being cured). While this is acceptable to cure painting of a single spot repair that is otherwise holding up an aircraft or part from reentering service, it is far insufficient to cure the dozens of stencil markings on an F-16 aircraft undergoing repaint. Either a small number of lamps would have to be moved around the aircraft to reach each marking (vastly reducing process time savings and increasing labor costs) or dozens of lamps would have to be operated simultaneously (again increasing labor costs and requiring commensurate amounts electrical power). In addition, though no standards COTS costs are available for explosion-proof UVA lamps, H&S Autoshot estimates the cost could be tens of thousands of USD per lamp.

Development of an automated system in which a high intensity full spectrum UV light were moved over a large part surface could allow fast enough cure to achieve process time savings. Engineering estimates are that such a system would cost $1.5 million USD or more to design and construct, depending on the size of the components accommodated. This cost does not include the floor space that would have to be permanently devoted to such a unit as well as the building modification costs necessary to ensure operator safety and power and air supply. As weapon systems SPOs have historically been conservative in adopting new coating systems for aircraft, it is likely any coating developed for such a system would require years of demonstration on an aircraft before being adopted into fleet usage.

7.2.5 Process Times Savings

The cost justification for UV-curable coatings primarily rests on process time savings. With a faster coating cure, aircraft and aircraft components can be returned to service quickly rather than waiting days for the paint to completely cure. However, repeated attempts to quantify the value of process time savings were unsuccessful. In a visit to OO-ALC on November 8, 2011, the issue was discussed in detail with maintenance personnel.

Currently maintenance organizations are given a set amount of time to complete tasks such as repaint, which incorporate current paint cure times into the planning process. If the total process time for maintenance turn-around could be reduced, a depot could offer this as a higher value service to the owning organization of an aircraft or other aerospace item, requesting that the maintenance process be funded at a higher value to accommodate the extra operational and capital costs of a UV cure process in return for faster return of the item. However, no cost negotiations are known to have been done on the value of such a faster return.

Potentially a UV-curable coating system might reduce facility constrainers by opening up more shop space. There are occasions when paint cure time means that the parts must stay in place, occupying space and preventing a new paint process from beginning. However, paint shop planning accommodates for paint cure time under normal circumstances. Facility constraints only come into play due to unexpected repaint to fix mistakes or when components are delayed entering into paint. These events occur irregularly and do not have a standard cost in shop records.

Some parts have a start to finish time where, after the part is stripped, it has to be primed within 48 hours, then have topcoat applied within 24 hours, then stenciled within 24 hours. Because this process is time dependent it cannot be started if it happens to fall on a weekend or holiday where the timing criteria cannot be met. This labor cost is a potential area for CBA savings, but again the value is nearly impossible to quantify due to the irregular nature of the occurrences.

8.0 IMPLEMENTATION ISSUES

8.1 Performance Issues

The stringent performance requirements of DoD aerospace coatings have been difficult to meet for UV-curable coatings. Current aerospace topcoats have increased in performance over the past few decades, until they reached their current status of high flexibility, high hardness and fluid resistance, low gloss, and long term resistance to UV degradation allowing aircraft to weather years of direct exposure to sunlight without fading of coloration. This performance has been extremely difficult for UV-curable coatings tested during this effort to match. The Deft 21BK001 evaluated during the initial screening testing came the closest to matching the current APC coatings in weathering resistance, and it still fell short in flexibility and gloss requirements.

Current aerospace coatings are moving targets which have seen improvements over the past year in longevity and general performance. Being able to match not merely the minimum specification requirements but the APC requirements has so far not been possible, and maintenance depots and aircraft SPOs will be reluctant to switch to any coating system which cannot equal current performance.

8.2 Application Issues

Testing over the course of this project has shown that UV-curable coatings are highly sensitive to a variety of application issues including coating thickness, UV exposure, and compatibility with solvent-based primers. Coating thickness and UV exposure are related issues, as a coating applied at a thickness over that for which the coating has been designed may mean that insufficient light is reaching the deepest part of the coating and it will never successfully cure. Similarly, if the UV exposure is misjudged such as from part of the painted area falling only at the edge of the lamp's illuminated area, the coating may not receive sufficient energy to cure. Many/most commercial processes utilizing UV-curable systems work with automated paint systems and lamp systems on regular production lines that can reliably apply coating and cure exposure in the same way on every part passing through. This differs from the majority of aircraft maintenance operations which act as batch processes in which coating is applied by operators with manually operated HVLP systems. Though trained painting technicians can apply coatings at a consistent thickness most of the time, the margins allowed by many UV-curable coatings seem very small. Similarly, distances of inches in positioning of a UV lamp can greatly reduce the UV light intensity.

Most aerospace topcoats must be timed correctly with application on primers. A primer that has not been allowed sufficient time to cure will not accept a topcoat layer, but one which has achieved full cure will require some reactivation before achieving proper adhesion. However, UV-curable topcoats appear to require more controlled timing than conventional coatings. The reason for this is that when a UV-curable coating is cured, it cures completely, hindering the primer from outgassing its solvent content and potentially causing bubbling and other effects if the primer has not been allowed enough cure time. The application window appears to differ based on the particular primer used, but in general is narrower than that of conventional topcoats.

A potential solution that has been investigated under other UV-curable aerospace efforts has been to produce a UV-curable coating one-coat that simultaneously offers the corrosion-protection properties of aerospace primers while giving the appearance and resistance properties of aerospace topcoats. However this would likely be extremely difficult to achieve given the difficulty of matching topcoat properties alone. There are currently no conventional isocyanate-based one-coat systems used in DoD aerospace.

Development of a UV-curable primer coating specifically designed to be paired with a UV-curable topcoat would be another potential solution. However, due to the DoD-wide requirement to implement hexavalent chromium reduction, any new primers introduced would have to be chrome-free. Formulating a chrome-free primer that can provide the required mil-spec corrosion protection has been a multi-year effort by the USAF, and again a UV-curable coating would be playing catch-up to existing coating performance.

An automated system such as was discussed in Section 7.2.4 might alleviate some application concerns. However, such a system would need to show acceptable payback from process time savings in order to justify implementation.

8.3 Approving Authorities

In the USAF, aircraft SPOs can authorize use of coating systems not qualified under a mil-spec. The original intent of this effort was to conduct long term on-aircraft demonstrations that would give SPOs technical data to support approval of UV-curable coatings in limited use on non-critical aircraft areas. It was expected that approving authorities in the USCG and USN would pursue similar implementation paths, with a UV-curable type being eventually added to MIL-PRF-85285 as sufficient demand and applications were found. Due to repeated inability to pass JTP performance testing, no such long term demonstrations were conducted under this effort. However, any future coating projects would be required to follow a similar approval path.

8.4 Procurement Issues

Currently, there is no identified UV-curable coating suitable for implementation. In the event that such a coating is developed, it is unlikely that any commercial vendor would offer it for sale as a COTS product until a regular demand has been established. Initial implementation would likely require ordering samples as special production batches from a batch coating manufacturer licensed to produce the coating. Because pigmentation can greatly affect UV curing properties, each individual color of a UV-curable aerospace coating would need to be tested after being formulated to a specific color.

In addition, a UV curing system suitable for usage with the coating and intended application would have to be procured. Costs on this would vary based on the nature of the system (fixed to a single location and targeted component versus a flexible system designed for usage with a variety of components). However, the system would need to be custom-built and tested regardless of its configuration.

9.0 REFERENCES

The following documents in Table 45 were referenced in this document.

Table 45. Reference Documents

Document	Name	Section	Date
MIL-PRF-85285D	Performance Specification Coating, Polyurethane, Aircraft and Support Equipment	All	2006
MIL-PRF-23377	Performance Specification Primer Coating: Epoxy, High-Solids	All	2006
MIL-PRF-32239	Coating System, Advanced Performance, for Aerospace Applications	All	2007
MIL-PRF-85570	Cleaning Compounds, Aircraft Exterior	Type II	2002
ASTM B 117	Standard Practice for Operating Salt Fog Apparatus	All	2009
ASTM D 2244	Standard Practice for Calculation of Color Tolerance and Color Differences form Instrumentally Measured Color Coordinates	All	2005
ASTM D 523	Standard Test Method for Specular Gloss	All	1999
ASTM D 3359	Standard Test Method for Measuring Adhesion by Tape Test	Test Methods A & B	2002/2009
ASTM D 3363	Standard Test Methods for Film Hardness by Pencil Test (D-3363)	All	2005/2011
ASTM D 7091	Standard Practice for Nondestructive Measurement of Dry Film Thickness of Nonmagnetic Coatings Applied to Ferrous Metals and Nonmagnetic, Nonconductive Coatings Applied to Non-Ferrous Metals	All	2005

Table 45 Reference Documents (Continued)

Document	Name	Section	Date
ASTM D 522	Standard Test Methods for Mandrel Bend Test of Attached Organic Coatings	All	1993
ASTM D 6905	Standard Test Method for Impact Flexibility of Organic Coatings	All	2003
ASTM G 155	Standard Practice for Operating Xenon Arc Light Apparatus for Exposure of Non-Metallic Materials	All	2005
ASTM D 2247	Standard Practice for Testing Water Resistance of Coatings in 100 % Relative Humidity	All	2002
CLG-LP-043-Rev 00	Stripability of Chemical Strippers (CTIO-developed specification)	All	2003

APPENDIX A - POINTS OF CONTACT

Table 46. Points of Contact

Point Of Contact	Organization	Phone / Email	Role in Project
John Jusko	OO-ALC/ENGO 6051 Gum Lane Bldg. 1225 Hill, AFB UT 84056	(801) 586-2090 John.jusko@hill.af.mil	Principal Investigator
Glen Baker	309 AMXG/EN 5875 South Gate Avenue Building 225 Hill AFB, Utah 84056	(801) 940-6261 Glen.baker2@hill.af.mil	Aircraft Coatings Application and Removal
Cody Hone	809 MXSS/MXDEA 7278 4th Street Bldg. 100 Bay D Hill Air Force Base, UTAH 84056	(801) 586-4515 Cody.hone@hill.af.mil	Materials Engineer
Thomas Naguy	AFRL	(937) 656-5709 thomas.naguy@wpafb.af.mil	Program Manager
Al Baum	CTC 100 CTC Drive Johnstown, PA 15904	(814) 269-2694 bauma@ctc.com	Project Lead
Matthew Campbell	CTC 2000 Technology Drive, 2nd Floor, Suite 205, Pittsburgh, PA 15219-15219	(412) 992-5382 Campbell@ctc.com	Technical Support
Randall Straw	CTC/AFRL	(937) 255-5598 randall.straw@wpafb.af.mil	Technical Support

APPENDIX B - SECOND ROUND SCREENING TEST DATA

Summary of Test Results for Minimum Performance								
Coating System								
Vendor Number	PH	Color	Color Match	Gloss Match	Wet Tape	Cross Hatch	Low Temp Flex	GE Impact
CONTROL Deft 03-GY-321	HB	Camo Gray 36173	Pass	Pass	Pass	Pass	Pass	Fail
CONTROL Deft 99-GY-001	HB	Camo Gray 36173	Pass	Pass	Pass	Pass	Pass	Fail
Deft 21-BK-001	F	Camo Black 37038	Fail	Fail	Pass	Pass	Pass	Fail
Bayer NB 954148	HB	Camo Black 37038	Fail	Fail	Pass	Fail	Pass	Fail
Bayer NB 954149	HB	Camo Black 37038	Fail	Fail	Pass	Pass	Pass	Fail
Bayer NB 954150	HB	Camo Black 37038	Fail	Fail	Pass	Fail	Pass	Fail
Red Spot UVX0724	B	Gloss White 17925	Fail	Fail	Fail	Fail	Pass	Fail
DSM Desotech DN-0197	HB	Gloss White 17925	Fail	Fail	Pass	Fail	Pass	Fail
DSM Desotech DN-0196	2B	Camo Gray 36173	Fail	Pass	Pass	Pass	Pass	Fail
Red Spot UVX0726	< 6B	Camo Gray 36173	Fail	Pass	Pass	Pass	Pass	Fail

Coating System		Weathering (500-hrs)		Post Test Low Temp Flexibility	Post Test GE Impact	Cleaning	Heat Resistance (1-hr 250 F)
Vendor Number	Sys	Color Change	Gloss Change				
CONTROL Deft 03-GY-321	A	Pass	Pass	Pass	*3	Fail	Pass
CONTROL Deft 99-GY-001	B	Pass	Pass	Pass	*3	Fail	Pass
Deft 21-BK-001	C	Pass	*1	Pass	*3	Not required	Pass
Bayer NB 954148	D	Pass	*1	Pass	*3	Not required	Pass
Bayer NB 954149	E	Pass	*1	Pass	*3	Not required	Pass
Bayer NB 954150	F	Fail	*1	Pass	*3	Not required	Pass
Red Spot UVX0724	G	Pass	*2	Fail	*3	Pass	Pass
DSM Desotech DN-0197	H	Fail	*2	Fail	*3	Pass	Fail
DSM Desotech DN-0196	I	Pass	Fail	Pass	*3	Fail	Pass
Red Spot UVX0726	J	Pass	*2	Pass	*3	Pass	Pass
*1 Initial gloss too high for valid test /*2 Initial gloss too low for valid test /*3 Initial elongation too low for							

Coating System		Lube Oil Resistance	Hydraulic Fluid Resistance (24-hr)	Jet Fuel Resistance (7-day)
Vendor Number	**Sys**			
CONTROL Deft 03-GY-321	A	Pass	Pass	Pass
CONTROL Deft 99-GY-001	B	Pass	Pass	Pass
Deft 21-BK-001	C	Pass	Pass	Pass
Bayer NB 954148	D	Pass	Pass	Pass
Bayer NB 954149	E	Pass	Pass	Pass
Bayer NB 954150	F	Pass	Pass	Pass
Red Spot UVX0724	G	Fail	Pass	Pass
DSM Desotech DN-0197	H	Pass	Pass	Pass
DSM Desotech DN-0196	I	Pass	Pass	Pass
Red Spot UVX0726	J	Pass	Pass	Pass

Color and Gloss Match

Coating		Color of System				Fed Std 595 Color		Results
Vendor Number	**Sys**	**Color**	**L***	**a***	**b***	**Color**	**ΔE**	**Minimum**
Deft 03-GY-321	A	Camo Gray	50.24	-1.41	-4.32	36173	0.3	Pass
Deft 99-GY-001	B	Camo Gray	49.94	-1.61	-4.40	36173	0.1	Pass
Deft 21-BK-001	C	Camo Black	25.81	0.43	-0.09	37038	3.5	Fail
Bayer NB 954148	D	Camo Black	25.40	0.30	-0.11	37038	3.1	Fail
Bayer NB 954149	E	Camo Black	25.36	0.32	-0.10	37038	3.1	Fail
Bayer NB 954150	F	Camo Black	25.27	0.30	-0.16	37038	3.0	Fail
Red Spot UVX0724	G	Gloss White	94.22	-1.37	3.63	17925	2.0	Fail
DSM Desotech DN-0197	H	Gloss White	78.80	-5.24	16.44	17925	19.0	Fail
DSM Desotech DN-0196	I	Camo Gray	47.44	-1.06	-3.26	36173	2.8	Fail
Red Spot UVX0726	J	Camo Gray	53.59	-1.06	-2.59	36173	4.1	Fail

Coating Passes	Full Failure
Marginal Failure	

Gloss Match of Coatings									
Coating			Gloss		Req. Gloss at 60°		Opt. at 60/85		Results
Vendor Number	Color	Sys	60°	85°	Min.	Max.	Min.	Max.	Minimum
Deft 03-GY-321	Camo Gray	A	1.4	2.8	-	6.0	-	5/9	Pass
Deft 99-GY-001	Camo Gray	B	1.3	2.4	-	6.0	-	5/9	Pass
Deft 21-BK-001	Camo Black	C	6.3	38.4	-	6.0	-	5/9	Fail
Bayer NB 954148	Camo Black	D	22.6	68.6	-	6.0	-	5/9	Fail
Bayer NB 954149	Camo Black	E	28.1	66.4	-	6.0	-	5/9	Fail
Bayer NB 954150	Camo Black	F	17.3	57.8	-	6.0	-	5/9	Fail
Red Spot UVX0724	Gloss White	G	36.4	NR	80.0	-	90/-	-	Fail
DSM Desotech DN-0197	Gloss White	H	71.2	NR	80.0	-	90/-	-	Fail
DSM Desotech DN-0196	Camo Gray	I	2.6	4.5	-	6.0	-	5/9	Pass
Red Spot UVX0726	Camo Gray	J	2.8	4.5	-	6.0	-	5/9	Pass

Coating Passes
Marginal Failure
Full Failure

Wet Tape Adhesion

Wet Tape Adhesion				
Coating			Adhesion	Results
Vendor Number	Color	Sys	Rating	Minimum
Deft 03-GY-321	Camo Gray	A	5A	Pass
Deft 99-GY-001	Camo Gray	B	5A	Pass
Deft 21-BK-001	Camo Black	C	5A	Pass
Bayer NB 954148	Camo Black	D	5A	Pass
Bayer NB 954149	Camo Black	E	4A	Pass
Bayer NB 954150	Camo Black	F	4A	Pass
Red Spot UVX0724	Gloss White	G	1A	Fail
DSM Desotech DN-0197	Gloss White	H	5A	Pass
DSM Desotech DN-0196	Camo Gray	I	4A	Pass
Red Spot UVX0726	Camo Gray	J	5A	Pass

Coating Passes
Marginal Failure
Full Failure

Cross Hatch Adhesion

Cross Hatch Adhesion				
Coating			Adhesion	Results
Vendor Number	Color	Sys	Rating	Minimum
Deft 03-GY-321	Camo Gray	A	4B	Pass
Deft 99-GY-001	Camo Gray	B	4B	Pass
Deft 21-BK-001	Camo Black	C	5B	Pass
Bayer NB 954148	Camo Black	D	3B	Fail
Bayer NB 954149	Camo Black	E	4B	Pass
Bayer NB 954150	Camo Black	F	1B	Fail
Red Spot UVX0724	Gloss White	G	0B	Fail
DSM Desotech DN-0197	Gloss White	H	3B	Fail
DSM Desotech DN-0196	Camo Gray	I	4B	Pass
Red Spot UVX0726	Camo Gray	J	4B	Pass

Coating Passes
Marginal Failure
Full Failure

Pencil Hardness

Pencil Hardness of Coating				
Coating			Hardness	Results
Vendor Number	Color	Sys	Pencil	
Deft 03-GY-321	Camo Gray	A	HB	Pass
Deft 99-GY-001	Camo Gray	B	HB	Pass
Deft 21-BK-001	Camo Black	C	F	Pass
Bayer NB 954148	Camo Black	D	HB	Pass
Bayer NB 954149	Camo Black	E	HB	Pass
Bayer NB 954150	Camo Black	F	HB	Pass
Red Spot UVX0724	Gloss White	G	B	Pass
DSM Desotech DN-0197	Gloss White	H	HB	Pass
DSM Desotech DN-0196	Camo Gray	I	2B	Fail
Red Spot UVX0726	Camo Gray	J	< 6B	Fail

Low Temperature Flexibility

Low Temperature Flexibility				
Coating			Evaluation	Results
Vendor Number	Color	Sys		Minimum
Deft 03-GY-321	Camo Gray	A	No cracking	Pass
Deft 99-GY-001	Camo Gray	B	No cracking	Pass
Deft 21-BK-001	Camo Black	C	No cracking	Pass
Bayer NB 954148	Camo Black	D	No cracking	Pass
Bayer NB 954149	Camo Black	E	No cracking	Pass
Bayer NB 954150	Camo Black	F	No cracking	Pass
Red Spot UVX0724	Gloss White	G	No cracking	Pass
DSM Desotech DN-0197	Gloss White	H	No cracking	Pass
DSM Desotech DN-0196	Camo Gray	I	No cracking	Pass
Red Spot UVX0726	Camo Gray	J	No cracking	Pass

Coating Passes
Marginal Failure
Full Failure

GE Impact Flexibility

GE Impact Elongation Percent					
Coating			Elongation	Required	Results
Vendor Number	Color	Sys	(%)	(%)	Minimum
Deft 03-GY-321	Camo Gray	A	10	40	Fail
Deft 99-GY-001	Camo Gray	B	5	40	Fail
Deft 21-BK-001	Camo Black	C	2	40	Fail
Bayer NB 954148	Camo Black	D	2	40	Fail
Bayer NB 954149	Camo Black	E	2	40	Fail
Bayer NB 954150	Camo Black	F	2	40	Fail
Red Spot UVX0724	Gloss White	G	1	40	Fail
DSM Desotech DN-0197	Gloss White	H	2	40	Fail
DSM Desotech DN-0196	Camo Gray	I	5	40	Fail
Red Spot UVX0726	Camo Gray	J	2	40	Fail

Coating Passes
Marginal Failure
Full Failure

500-hr Accelerated Weathering Effect on Color				
Coating			ΔE	Results
Vendor	Color	Sys		Minimum
Deft 03-GY-321	Camo Gray	A	0.3	Pass
Deft 99-GY-001	Camo Gray	B	0.0	Pass
Deft 21-BK-001	Camo Black	C	0.2	Pass
Bayer NB 954148	Camo Black	D	0.9	Pass
Bayer NB 954149	Camo Black	E	0.8	Pass
Bayer NB 954150	Camo Black	F	1.2	Fail
Red Spot UVX0724	Gloss White	G	1.0	Pass
DSM Desotech DN-0197	Gloss White	H	1.7	Fail
DSM Desotech DN-0196	Camo Gray	I	0.4	Pass
Red Spot UVX0726	Camo Gray	J	0.1	Pass

500-hr Accelerated Weathering 60° Gloss				
Coating			Init Gloss	Final Gloss
Vendor	Color	Sys		
Deft 03-GY-321	Camo Gray	A	1.4	1.3
Deft 99-GY-001	Camo Gray	B	1.3	1.2
Deft 21-BK-001	Camo Black	C	6.3	3.6
Bayer NB 954148	Camo Black	D	22.6	10.5
Bayer NB 954149	Camo Black	E	28.1	13.5
Bayer NB 954150	Camo Black	F	17.3	9.1
Red Spot UVX0724	Gloss White	G	36.4	31.2
DSM Desotech DN-0197	Gloss White	H	71.2	63.9
DSM Desotech DN-0196	Camo Gray	I	2.6	5.7
Red Spot UVX0726	Camo Gray	J	2.8	7.0

3000-hr Accelerated Weathering Effect on Color				
Coating			ΔE	Results
Vendor	Color	Sys		
Deft 03-GY-321	Camo Gray	A	1.7	Fail
Deft 99-GY-001	Camo Gray	B	0.2	Pass
Deft 21-BK-001	Camo Black	C	0.3	Pass
Bayer NB 954148	Camo Black	D	3.1	Fail
Bayer NB 954149	Camo Black	E	3.2	Fail
Bayer NB 954150	Camo Black	F	0.4	Pass
Red Spot UVX0724	Gloss White	G	0.7	Pass
DSM Desotech DN-0197	Gloss White	H	3.8	Fail
DSM Desotech DN-0196	Camo Gray	I	0.5	Pass
Red Spot UVX0726	Camo Gray	J	Coating destroyed	Fail

3000-hr Accelerated Weathering Effect on 60° Gloss				
Coating			Init Gloss	Final Gloss
Vendor	Color	Sys		
Deft 03-GY-321	Camo Gray	A	1.4	1.3
Deft 99-GY-001	Camo Gray	B	1.3	1.2
Deft 21-BK-001	Camo Black	C	6.7	2.1
Bayer NB 954148	Camo Black	D	21.9	6.0
Bayer NB 954149	Camo Black	E	30.6	10.8
Bayer NB 954150	Camo Black	F	16.2	6.2
Red Spot UVX0724	Gloss White	G	37.2	2.4
DSM Desotech DN-0197	Gloss White	H	72.8	9.8
DSM Desotech DN-0196	Camo Gray	I	2.4	7.6
Red Spot UVX0726	Camo Gray	J	2.6	Coating destroyed

Cleanability				
Coating			Cleanability	Results
Vendor Number	Color	Sys	Percent	Minimum
Deft 03-GY-321	Camo Gray	A	62	Fail
Deft 99-GY-001	Camo Gray	B	36	Fail
Deft 21-BK-001	Camo Black	C	Not tested	Not tested
Bayer NB 954148	Camo Black	D	Not tested	Not tested
Bayer NB 954149	Camo Black	E	Not tested	Not tested
Bayer NB 954150	Camo Black	F	Not tested	Not tested
Red Spot UVX0724	Gloss White	G	80	Pass
DSM Desotech DN-0197	Gloss White	H	81	Pass
DSM Desotech DN-0196	Camo Gray	I	5	Fail
Red Spot UVX0726	Camo Gray	J	80	Pass

APPENDIX C - DSM DESOTECH MONTH BY MONTH PROGRESS

February/March 2009 Progress
DSM accomplished the following in February/March 2009:

Accomplishments for February/March
- Fresh samples of oligomer and coating (DN-0197) were prepared in the lab.
- Instron mechanical properties (tensile strength, modulus, & elongation) and dynamic mechanical analysis testing (glass transition temperature & equilibrium modulus) of cured films were conducted to establish baseline properties, especially for flexibility.
- Seven variations of DN-0197, using combinations of alternate oligomer candidates and concentrations, were prepared. The variations were designed particularly to improve cured film flexibility. In all cases, liquid viscosity was found to be too high for efficient spray application. Despite this deficiency, mechanical properties were still recorded for comparison to the benchmark, DN-0197.

Current and/or Expected Problems
- Reduce viscosity sufficiently to allow for spray application while maintaining oligomer concentration to improve flexibility
- Optimize oligomer concentration for fluid resistance and gloss while maintaining viscosity for spray
- Overcome surface oxygen inhibition to enable adequate cure without degrading from resistance to weathering

Status of Deliverables
Following are targeted improvements needed over first submission of DN-0197
- Flexibility –test by Gardner impact and need to improve both mandrel bend & reverse impact results
- Gloss – need to achieve 90 rating at 60 degree observation angle
- Color & hiding – better opacity and match to Fed Std 595C (17860) needed
- Weathering – improve gloss retention after 1000 hrs in QUV (UVA + condensation) weathering
- Adhesion – maintain consistent 4/5 rating
- Fluid resistance – improve drop in pencil rating, especially in water & Skydrol

April Progress
DSM accomplished the following in April 2009:

Accomplishments for April
- Spray trials of two of the lowest viscosity coatings from March development gave very flat and poor looking films. The formulations from last month's work were designed particularly to improve flexibility of the cured film, however, the liquid viscosity was

found to be too high for efficient spray application. These trials were attempted to determine whether a viscosity of 1000 mPa·s could possibly be sprayed.

- Several reformulations were designed for lower viscosity. The variations included alternate lower viscosity oligomers. In each case, the resulting viscosity was slightly more than half the previous value. These coatings now range in viscosity from about 700 mPa·s to about 450 mPa·s. This range is more practical for spray application,.

<u>Current and/or Expected Problems</u>

- Maximizing oligomer concentration for flexibility while minimizing viscosity for spray
- Maintaining optimum oligomer concentration for crosslink density and fluid resistance while maintaining viscosity for spray
- Overcoming surface oxygen inhibition for full cure without the use of additives that will degrade from weathering resistance

<u>Status of Deliverables</u>

Following continue to be targeted improvements over DN-0197 benchmark

- Flexibility – need to improve both mandrel bend & reverse Gardner impact
- Gloss – need to achieve 90 rating at 60 degree observation angle
- Color & hiding – better opacity and match to Fed Std 595C (17860) needed
- Weathering – improve gloss retention after 1000 hrs in QUV (UVA + condensation) weathering
- Adhesion – maintain consistent 4/5 rating
- Fluid resistance – improve drop in pencil rating, especially in water & Skydrol

May Progress

DSM accomplished the following in May 2009:

<u>Accomplishments for May</u>

- Determined that a viscosity less than about 500 mPa·s is required for adequate spray atomization. This finding has allowed narrowing selection of alternate oligomer candidates to two.

- Using the two oligomers, developed two candidate coatings at lower viscosity. One candidate has a viscosity of about 350 mPa·s and sprays very efficiently. The second candidate has a viscosity of about 500 mPa·s and sprays adequately. However, the cured film of the second coating is not as glossy.

- Began preliminary cure studies on the two candidate coatings using the H&S AutoShot UVA 400 lamp assembly with intent to determine the optimum conditions for curing the coating. Determined the UVA irradiance at various distances from the substrate and the total energy at various exposure times. Determined that the second developmental coating cures somewhat faster than the first candidate.

- Determined the mechanical properties of the candidate coatings relative to the benchmark DN-0197 when cured under the UVA lamp. Found both candidates to be roughly comparable to DN-0197 in modulus and elongation.

Current and/or Expected Problems

- Overcoming oxygen inhibition to achieve complete cure at the surface and throughout the film without the use of additives that degrade from weathering resistance
- Obtaining sufficient thru-cure to achieve complete adhesion to the primer and to the anodized substrates
- Maintaining high gloss after cure in air at relatively low lamp intensity
- Balancing crosslink density to obtain sufficient fluid resistance while maintaining flexibility

Status of Deliverables

Following are the improvements needed over DN-0197 benchmark

- Flexibility – need to improve both mandrel bend & reverse Gardner impact
- Gloss – need to achieve 90 rating at 60 degree observation angle
- Color & hiding – better opacity and match to Fed Std 595C (17860) needed
- Weathering – improve gloss retention after 1000 hrs in QUV (UVA + condensation) weathering
- Adhesion – maintain consistent 4/5 rating
- Fluid resistance – improve drop in pencil rating, especially in water & Skydrol

As of May 2009, DSM continued to struggle with viscosity issues. Still no testing or development had been conducted for other aerospace requirements such as gloss, opacity, or adhesion. During teleconferences, CTC expressed a desire that DSM begin testing such properties on their new oligomers candidates for awareness of where they stood in regards to requirements. In particular, CTC expressed concern that none of the coating alternatives had yet even been tested on primed panels. DSM reiterated a determination to settle on an oligomer mixture for viscosity before tackling those issues.

June Progress

DSM accomplished the following in June 2009:

Accomplishments for June

- Candidate coatings 0574-130CG and 0606-138CG were selected for extended trial. Each has a viscosity around 350 mPa·s and can be effectively applied by spray with a HVLP gun. Candidate 0574-138CG was based on an oligomer having lower acrylate functionality compared to candidate 0606-138CG.

- Cure studies indicate that both coatings could be cured with the H&S Autoshot UVA 400 set at a distance of 10 inches and exposed for 10 minutes or at a distance of 6 inches for 5 minutes. When using the former settings, the peak temperature was measured at 63°C (~

140°F). Coating 0606-168CG was slightly better cured than coating 0574-130CG as measured qualitatively by surface marring with a thumb.

- Both coatings were spray applied to 2024-T3 aluminum having the epoxy primer reactivated by light sanding and solvent wiping according to the recommended reactivation procedure. Each coating was completely removed when subject to the cross-hatch adhesion test. Re-evaluation of the benchmark coating (DN-0197) previously shown to demonstrate good cross-hatch adhesion also indicated complete intercoat failure. This prompted reconsideration of the reactivation procedure and a modification to eliminate the sanding step was established. This modification resulted in excellent cross-hatch adhesion for the benchmark. Neither candidate had acceptable intercoat adhesion when re-tested with the modified reactivation procedure.
- Initial modification of coating 0606-138CG with increased adhesion promoter (0606-138CP) indicated excellent intercoat adhesion and a pencil rating of B-HB. However, it was desirable to lower the concentration for fear of introducing water sensitivity. Additionally, hiding still needs improvement, but gloss looks to be adequate.

Current and/or Expected Problems

- Reduce adhesion promoter for effective intercoat adhesion & good water resistance
- Increasing pigment concentration for good hiding while maintaining viscosity and through cure
- Balancing crosslink density to obtain sufficient fluid resistance while maintaining flexibility
- Overcoming oxygen inhibition to achieve complete cure at the surface and throughout the film without the use of additives that degrade from weathering resistance

Status of Deliverables

Following are the improvements needed over DN-0197 benchmark

- Flexibility – need to improve both mandrel bend & reverse Gardner impact
- Gloss – need to achieve 90 rating at 60 degree observation angle
- Color & hiding – better opacity and match to Fed-Std-595C (17860) needed
- Weathering – improve gloss retention after 1000 hrs in QUV (UVA + condensation) weathering
- Adhesion – maintain consistent 4/5 rating
- Fluid resistance – improve drop in pencil rating, especially in water & Skydrol

July Progress

DSM accomplished the following in July 2009:

Accomplishments for July

- Continued to struggle with variable intercoat adhesion to primed 2024-T3 aluminum panels. Utilizing high concentration of adhesion promoter as used in the benchmark coating DN-0197. Reducing the level of adhesion promoter does not seem to greatly improve adhesion.

- Increasing the pigment concentration by two percent relative to the benchmark gives the added hiding expected. Fortunately, the viscosity was still low enough to allow for effective spray application.
- Continue to see excellent adhesion on anodized 2024-T0 aluminum and have done some flexibility testing with two resin candidates and DN-0197 as a control. As expected, the higher functionality oligomer results in flexibility very similar to the benchmark which also contains a high functionality oligomer. The lower functionality oligomer gives much improved flexibility on 2024-T0 but intercoat adhesion on primed 2024-T3 is still poor.
- Began weathering resistance testing with the benchmark and with the best coating using the more flexible oligomer.

Current and/or Expected Problems

- Balancing crosslink density to obtain good fluid resistance without compromising flexibility
- Overcoming oxygen inhibition to achieve complete cure at the surface and throughout the film without the use of additives that degrade from weathering resistance

Status of Deliverables

Following are the improvements needed over DN-0197 benchmark

- Flexibility – need to improve both mandrel bend & reverse Gardner impact
- Gloss – need to achieve 90 rating at 60 degree observation angle
- Color & hiding – better opacity and match to Fed Std 595C (17860) needed
- Weathering – improve gloss retention after 1000 hrs in QUV (UVA + condensation) weathering
- Adhesion – maintain consistent 4/5 rating
- Fluid resistance – improve drop in pencil rating, especially in water & Skydrol

APPENDIX D - CURE-TEK 2400W CURE TESTING

UV-Curable coating Lamp Testing 11/18/2009 & 11/19/2009

UV-Curable Coatings Utilized:
Deft 21BK003 Topcoat (Fed Std 595B # 37038 Camouflage Black)

The lamp utilized was the H&S Autoshot Cure-Tek 2400W. Heads are identified as “left” and “right” when facing in same direction as the lamp. Five minutes was allowed as a warm-up time after the lamp was turned on for the lamp heads to reach maximum intensity. The cure area of the lamps is shown below. The numbers represent various locations beneath the lamps to be referenced later. Figure 26 shows the area.

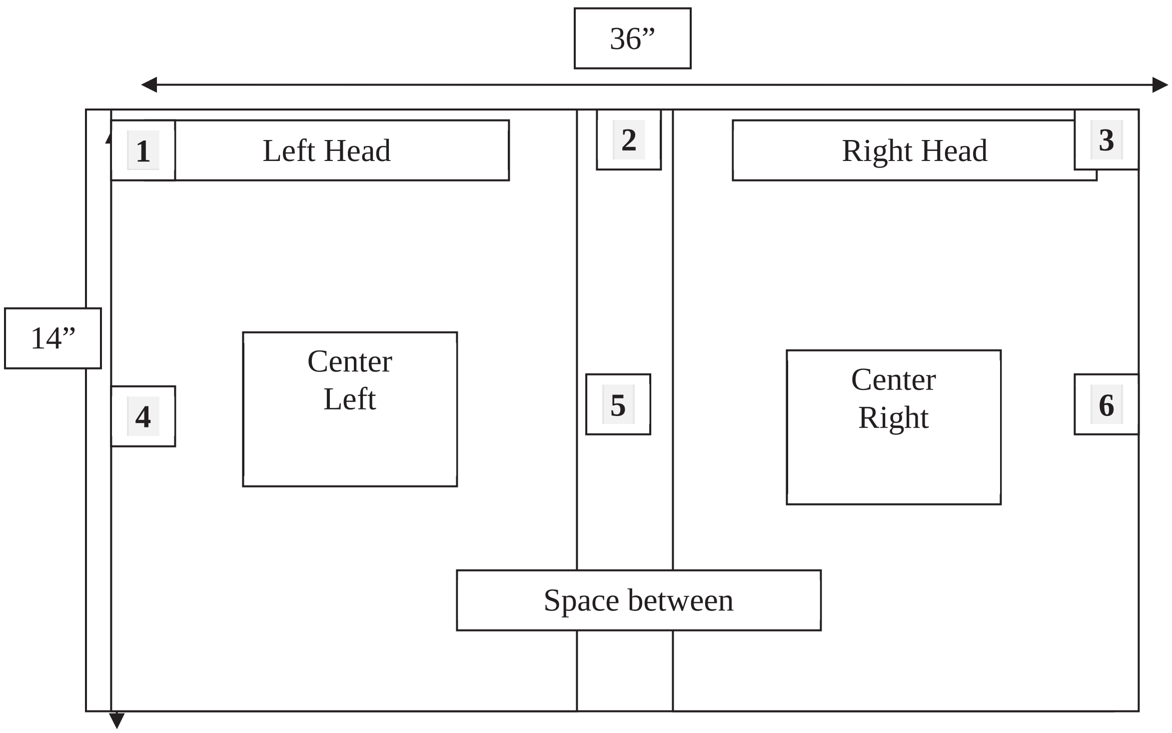


Figure 26. Identified Areas Beneath Cure-Tek 2400W Lamp heads

UV energy readings were taken with UV Power Puck® High Energy UV Integrating Radiometer, manufactured by EIT. Readings were in form of total energy as mJ/cm^2 (which is a function of time) and peak irradiance as mW/cm^2 (showing the maximum power the puck received at any point during its exposure). The power puck gives readings for the UVA, UVB, UVC, and UVV ranges separately. In general, only UVA and UVV energy was emitted, as the lamp is designed to filter other frequencies. Unless otherwise noted, all numbers given are for the UVA range. The Power Puck reads to three decimal places, but due to considerable noise in the readings, all data is rounded to the nearest tenth.

All painting was done on panels of 2024-T3 Aluminum (4" x 6" x 0.020") with ¼" hole in center of short side, coated with an Alodine 1200S chrome pretreatment many weeks in the past, when originally ordered. For panels to be coated with the Bayer flat black UV cure coating, a MIL-PRF-23377J, Type I, C2 primer had been applied. The primer was applied at 3:00 pm on Monday, November 17th.

MEK Rub testing: All MEK rub testing was done as 50 passes (25 double rubs) with the MEK-soaked rag wrapped around the head of a 32 ounce ball peen hammer. The ball side of the hammer head was wrapped with a lint free cotton rag. The wrapped head of the hammer was allowed to rest freely on the panel, dragged back and forth by gentle pushes and pulls of the handle. In this way a consistent and repeatable weight was applied to all rub passes.

11/18/2009

After both lamp heads were turned on and allowed to warm up for five minutes, peak irradiance readings were taken for the Center Left and Center Right areas under each head at a stand-off distance of 8-inches, as well as between the heads. Readings are shown in Table 47. Note that in some cases, the radiometer was not sensitive enough to provide a peak power number, indicated by "NM" (no measurement).

Table 47. Cure-Tek 2400W Power Readings

Center Left (mW/cm^2)	Center Right (mW/cm^2)	Between heads (mW/cm^2)
70.9	61.9	Too low to read (2690.1 mJ/cm^2 at 12 minutes)
70.6	62.5	NM
70.6	63.1	NM
70.2	63.8	NM
69.6	63.5	NM

At this point in the procedure, the lamp heads may have been at slightly different heights, explaining the difference in readings. Later in the process, a level was used to ensure that the lamp heads remained at equal stand-off distances. Figure 27 shows the lamp in position to cure.

Figure 27. 2400W Lamp Set-Up to Cure Panels

Figure 28 shows the lamp in operation.

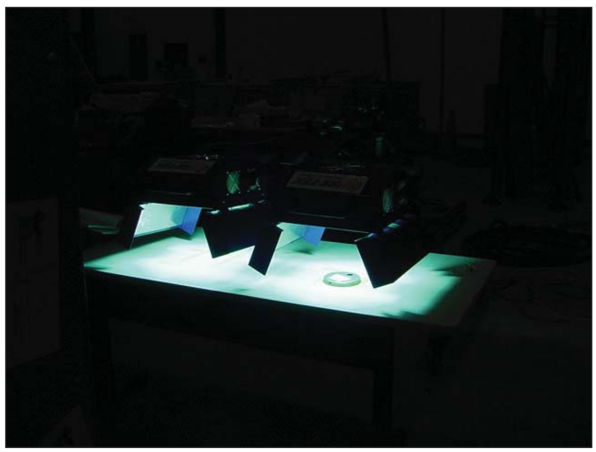


Figure 28. 2400W During CTC Cure Testing

Black Topcoat 21BK003

The application instructions given for 21BK003 state that:

> "Coating may be applied over properly cleaned composite surfaces, epoxy primer coatings or polyurethane coatings. Spray apply the topcoat using two to four coats to a total dry film thickness of 1.7 – 2.3 mils. Apply the first coat as a light (mist) coat. Allow the coat to set for 15 minutes (depending on airflow, temperature and humidity) before applying the second coat to permit solvent evaporation. Apply the second coat in a full wet coat to achieve the desired film thickness. Conventional, Air, Air Assisted Airless, HVLP, Electrostatic spray equipment may be used to apply this material."

To gain experience spraying the topcoat, three chromated (not primed) panels were chosen for use. These were labeled: PR-01, PR-02, and PR-03. For PR-01, all four coats were applied simultaneously without waiting for the mist coat to flash off. For PR-02 and PR-03, the mist coat was applied and allowed proper flash-off time before subsequent coatings were applied. Observation was that the application of the mist coat first produced a better spray, and all subsequent 21BK003 applications were made with a mist coat first.

The first factor tested was flash-off time. The curing instructions state that the coating should be allowed a 15 minute flash-off time before being exposed to UV light. The flash off time is required to allow solvent to evaporate so it will not become trapped in the cured coating. 21BK003 topcoat was applied to panels primed with a MIL-PRF-23377J, Type I, C2 primer. Each set of flash-off panels was allowed a different amount of flash-off time after spray before being cured. All of them were cured for 12 minutes at 8 inches stand-off distance, as specified in manufacturer instructions. They were then subjected to an MEK rub test. The table below shows the panels and the results.

Table 48. 21BK003 at Varying Flash-Off Times

Panel Code	Cured At	Description	MEK Rub Result	Average Dry Film Thickness (DFL) in mils
01-01	Center Right	0 flash-off time allowed	Some topcoat on rag; no wear-through to primer. Pass.	2.03
01-02	Center Left		Some topcoat on rag; no wear-through to primer. Pass.	2.28
02-01	Center Right	7 minutes flash-off time allowed	Some topcoat on rag; no wear-through to primer. Pass.	2.36
02-02	Center Left		Some topcoat on rag; no wear-through to primer. Pass.	2.46
03-01	Center Right	15 minutes flash-off time allowed	Some topcoat on rag; no wear-through to primer. Pass.	2.36
03-02	Center Left		Some topcoat on rag; no wear-through to primer. Pass.	2.36

Results were nearly identical in all cases, with all panels passing the MEK rub test.

Next a series of primed, 21BK003 topcoated panels were cured at different stand-off distances and cure times, followed by the MEK rub test. Results are shown in the table below.

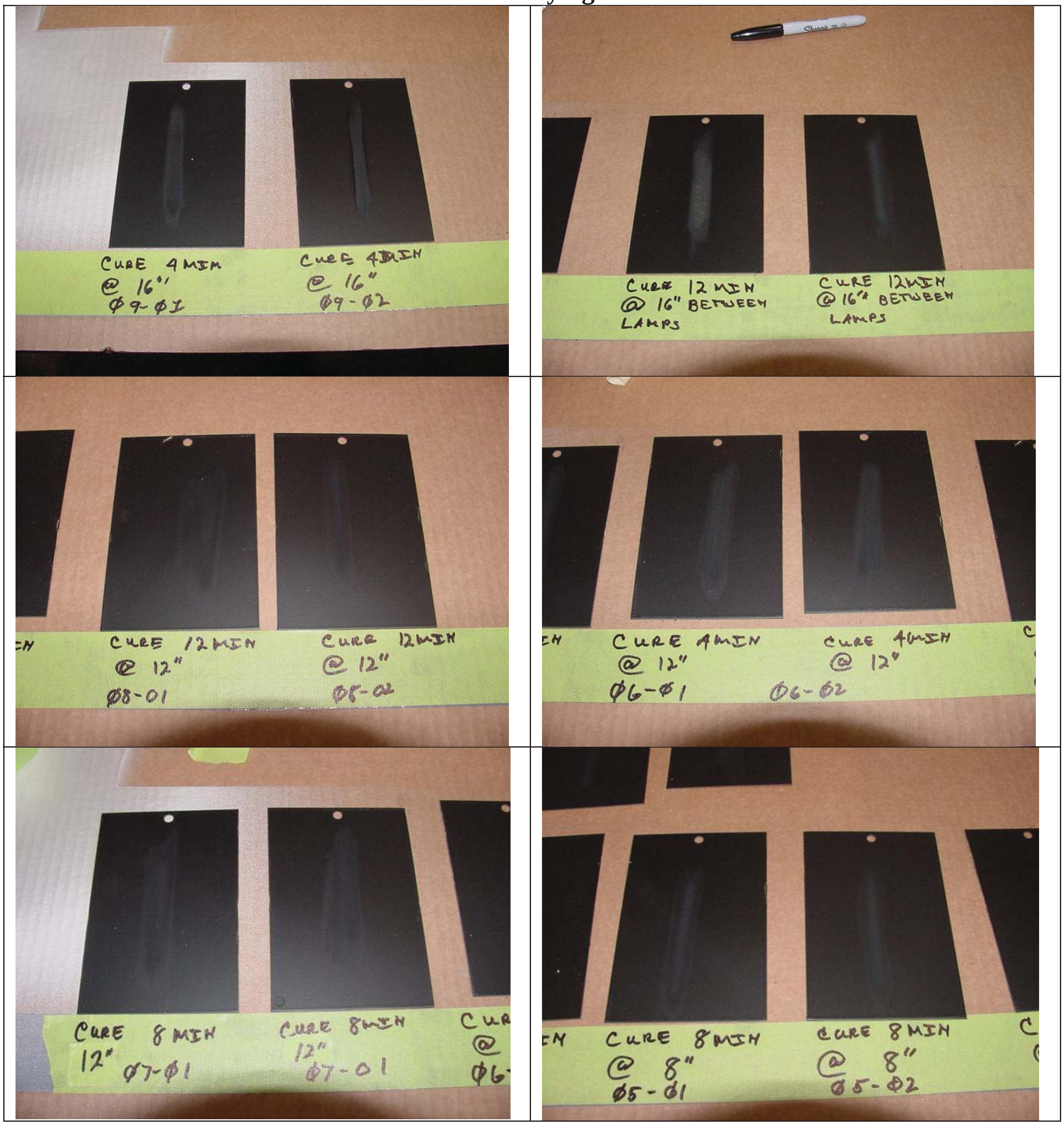
Table 49. 21BK003 at Varying Stand-offs and Cure Times

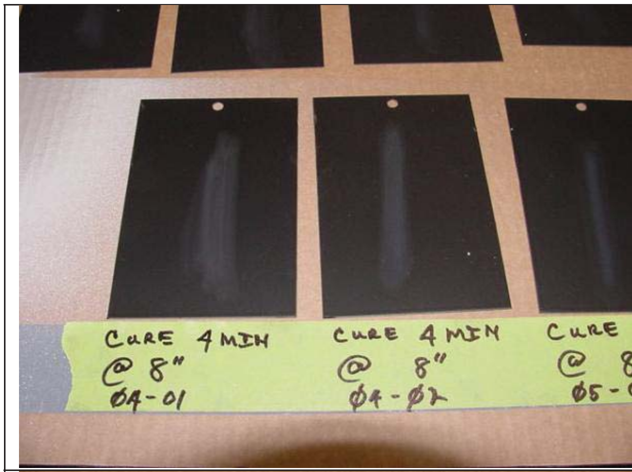
Panel Code	Cured At	Description	MEK Rub Result	Average DFL in mils
04-01	Center Left	4 minutes cure at 8 inches stand-off	Some topcoat on rag; no wear-through to primer. Pass. (both panels)	2.56
04-02	Center Right			2.92
05-01	Center Left	8 minutes cure at 8 inches stand-off	Some topcoat on rag; no wear-through to primer. Pass. (both panels)	2.70
05-02	Center Right			2.88
06-01	Center Left	4 minutes cure at 12 inches stand-off	Slightly more topcoat than in other trials on rag; no wear-through to primer. Pass. (both panels)	2.72
06-02	Center Right			2.68
07-01	Center Left	8 minutes cure at 12 inches stand-off	Some topcoat on rag; no wear-through to primer. Pass. (both panels)	2.56
07-02	Center Right			2.98
08-01	Center Left	12 minutes cure at 12 inches stand-off	Some topcoat on rag; no wear-through to primer. Pass. (both panels)	2.84
08-02	Center Right			2.80
09-01	Center Left	4 minutes cure at 16 inches stand-off	Much topcoat on rag, but no primer exposure. Pass. (both panels)	2.54
09-02	Center Right			2.50
10-01	Between lamps	12 minutes cure at 16 inches stand-off	Small exposure of primer for failure.	2.12
10-02	Between lamps		Barely passed rub.	2.34
11-01	Between lamps	8 minutes cure at 12inches stand-off	Some topcoat on rag; no wear-through to primer. Pass. (both panels)	2.30
11-02	Between lamps			2.42
12-01	Area #1	12 minutes cure at 10 inches stand-off	Some topcoat on rag; no wear-through to primer. Pass. (both panels)	2.32
12-02	Area #3			2.33
13-01	Area #4	12 minutes cure at 10 inches stand-off	Some topcoat on rag; no wear-through to primer. Pass. (both panels)	2.31
13-02	Area #6			2.20
14-01	Area #2	12 minutes cure at 10 inches stand-off	Some topcoat on rag; no wear-through to primer. Pass. (both panels)	2.28
14-02	Opposite side form area #2			2.34

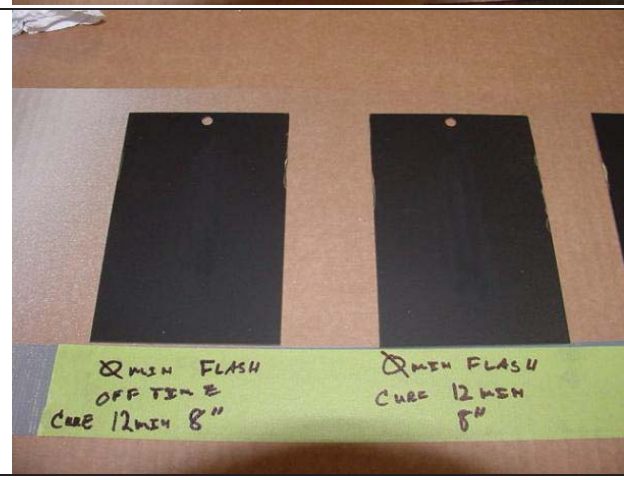
As can be seen, it was difficult to force an MEK rub failure from this topcoat. There was only one MEK failure; however there was some topcoat removed on all panels.

Table 50 shows the panels

Table 50. 21BK003 Pictures at Varying Cure Times and Stand-Off







The MEK rub was performed within a few minutes after the panel had been removed from under the lamp. During this time period, various power and energy readings were taken using the radiometer to determine what UV exposure the panels were receiving. These readings are shown below. As before, in some cases the radiometer was not sensitive enough to provide a peak power number, indicated by "NM". Results are shown in the table below.

Table 51. Cure-Tek 2400W Intensity at Varying Stand-off Distances

Stand-Off Distance	Position	Energy @ 20 seconds [mJ/cm^2]	Peak Power [mW/cm^2]
12"	Center Left	442.2	30.3
12"	Center Right	540.9	31.3
12"	Area #5	209.1	NM
16"	Center Left	264.7	NM
16"	Area #5	135.9	NM

<u>11/19/2009</u>

Stencil Cure

Six panels primed with MIL-PRF-23377J, Type I, C2 primer had a solvent-borne MIL-PRF-85285 APC topcoat applied to them so that the 21BK003 could be tested as a stencil coating on the APC. They were topcoated with APC and then allowed to cure overnight. Stencil maskant reading "This Is a Test" in 1/2-inch high letters were applied diagonally across the center of the panels, and the rest of the panel area was masked off to prevent overspray on the rest of the panel. The 21BK003 was applied using a small touch-up or stencil spray gun then sprayed over the maskant and cured for various lengths of time at a distance of 8 inches or 12 inches stand-off. The maskant was then removed, with results as shown below.

Table 52. 21BK003 Tested as Marking Coating

Panel Code	Cured At	Description	MEK Rub Result
15-01	Center Left	1 minutes cure at 8 inches stand-off	Maskant peeled with no damage to stencil lettering. The coating was a little tacky but would not come off on your hand.
16-01	Center Left	2 minutes cure at 8 inches stand-off	Maskant peeled with no damage to stencil lettering. Some bubbling of maskant, possibly due to heat.
17-01	Center Left	3 minutes cure at 8 inches stand-off	Maskant peeled with no damage to stencil lettering. Some bubbling of maskant, coating seemed dry.
18-01	Center Left	4 minutes cure at 8 inches stand-off	Maskant peeled with no damage to stencil lettering. Some bubbling of maskant, coating definitely dry.
19-01	Center Left	8 minutes cure at 8 inches stand-off	Left to sit for two hours before maskant removed. Maskant peeled with no damage to stencil lettering.
20-01	Center Left	8 minutes cure at 12 inches stand-off	Left to sit for two hours before maskant removed. Maskant peeled with no damage to stencil lettering.

Figure 29. Panel 19-01

Figure 30. Panel 18-01

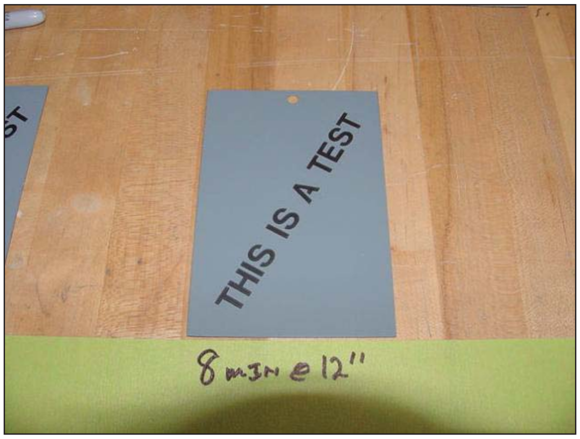


Figure 31. Panel 20-01

A reading was taken with the radiometer at the Center Left position for 20 seconds at the 8 inches stand-off used above. It recorded 979.4 mJ/cm^2 and a peak of 55.1 mW/cm^2. More readings on the lamp were taken in different areas. This was completed to see how much if any lamp intensity dropped off in what appeared to be the curable area.

Table 53. Additional Cure-Tek 2400W Intensity Readings

Stand-Off Distance	**Position**	**Energy @ 20 seconds [mJ/cm^2]**	**Peak Power [mW/cm^2]**
8”	Area #1	424.8	30.0
8”	Area #1	459.9	31.0
8”	Area #1	468.7	28.0
8”	Area #2	130.5	NM
12”	Area #1	305.8	22.6
12”	Area #1	283.1	21.6
12”	Area #1	294.1	21.6
12”	Area #2	325.8	23.8
12”	Area #2	305.6	23.2
12”	Area #2	297.3	23.2
12”	Area #3	392.9	26.7
12”	Area #3	380.3	24.8
12”	Area #3	396.6	25.8
12”	Area #5	228.0	NM
12”	Area #5	244.0	NM
12”	Area #5	252.5	21.6
12”	Area #4	235.2	NM
12”	Area #4	221.5	NM
12”	Area #6	260.8	NM
12”	Area #6	278.9	NM
12”	Area #6	275.0	21.9

APPENDIX E - JTP TEST DATA FROM BMS/DEFT FLAT COATINGS

JTP Test Results Analysis

1. Introduction:

Samples of the three UV-curable coatings manufactured by Deft coatings, along with appropriate control coatings, were tested according to the JTP at Battelle Memorial Laboratories from approximately December 2009 through July 2010. This document discusses the test results.

2. Test Parameters

2.1. Coatings Evaluated:

The Deft UV-curable topcoats to be evaluated were mixed for the Dem/Val in November 2009 (for the 36173 Gray and 37038 Black) and December 2009 (for the 36118 Gray). The Deft identification numbers, FED-STD-595 color numbers, and Deft Batch numbers are listed in Table 54.

Table 54. Deft UV-Curable Topcoats

Deft Identification	Color	Batch Number
21GY001	36173 Gray	200-63
21GY002	36118 Gray	200-64
21BK003	37038 Black	200-65

For ease of readability and familiarity, these Deft formulations will henceforth be referred to by their FED-STD-595 color numbers from this point forward. For instance, 21GY002 will be referred to as, “Deft UV Gray 36118” or simply “UV Gray 36118”.

In addition, three control coatings were evaluated. These coatings were black and solvent-borne topcoats manufactured by Deft Coatings, all of which are on the Qualified Products List (QPL) for MIL-PRF-85285. They are shown in Table 55, with the description, listing of which type and class each is on the QPL for, and of each in testing.

Table 55. Control Coatings

Color	QPL Designated	Function
Control Gray 36173	Type I, Class H	Minimum requirements for gray
Control Black 37038	Type I, Class H	Minimum requirements for black
Control Gray 36173 (APC)	Type IV, Class H	Optimum requirements

2.2. Application and Cure Parameters:

The coatings were applied using a High Volume Low pressure (HVLP) paint application system on panels laid vertically. Cure of the UV-curable coatings was also conducted vertically. Cure was conducted using an H&S Autoshot 1200W lamp system at a stand-off distance of 8 inches for 8 minutes. Six panels of size 3" by 6" were cured at one time in a 9" by 12" grid.

It should be noted that the Deft UV Gray 36118 was the first UV-curable coating which Battelle attempted to apply and cure. During this first attempt, the UV gray 36118 was sprayed out on panels on a vertical rack. The coatings on these panels began to sag and drip before coating cure was effected, ruining the panels for testing purposes and depleting the supply of coating. In addition, the 36118 suffered from pigment float where the blue pigment quickly separated out from the coating, even shortly after mixing.

To address these concerns, Deft mixed a new batch of UV Gray 36118 and submitted it for later application. This new batch had an anti-sag agent, new dispersant, and correction to eliminate pigment float. Because of time constraints, the new coating was not fully colored matched to FED-STD-595. These changes were considered to be unlikely to alter coating performance properties, and all future batches of the UV Gray 36118, as well as the UV Gray 36173 and the UV Black 37038, will incorporate the anti-sag, new dispersant, and (for the UV Gray colors) the pigment float correction agent.

3. Test Data and Analysis

3.1. Discussion Format:

Each performance test will be discussed in the following manner. First, the relevant section of the JTP will be summarized, and the minimum and optimum performance requirements will be listed. Then the results of the testing will be listed in a tabular format. Finally, an analysis section will review the results. For each JTP test analysis, several important items must be considered. These are:

1) What was the desired performance specification and how did the UV-curable coatings perform against it?

2) How did the UV-Curable coatings perform when compared against the control coatings?

3) What factors may be affecting coating performance?

The first and second items will be discussed on a case-by-case basis for each test. Results not meeting spec will be italicized and shown in red in the data table. However, it is notable that for many tests, the UV-curable coating samples have shown inferior performance to that suggested by laboratory data provided by the manufacturer. In discussions with the manufacturer, Deft Coatings, regarding these results, it has been suggested that the properties of UV-curable coatings are sensitive to being applied in a thickness over that recommended by the military specification and vendor technical data sheet. The manufacturer states that high thickness may prevent complete cure of the coating. Consequently, the coating stack-up thickness for each sample panel will be listed below the panel and color coded. (It is assumed that the primer will have been applied within spec, at a thickness of no more than 0.9 mils.) These coating thicknesses will be color coded in the following fashion:

Table 56. Stack-Up Thickness Visual Coding

Coating Stack-Up Thickness	Visual Coding
2.3 to 3.2 mils (spec required thickness)	Thickness noted in black.
3.3 to 4.2 mils (one mil or less over spec)	Thickness noted in orange.
4.3 to 5.2 mils (between one and two mils over spec)	Thickness noted in red.
5.3+ mils (greater than two mils over spec)	**Thickness noted in bolded red.**

No panels were found that were applied at a thickness of less than 2.3 mils, except for certain flexibility panels that were given a topcoat only and will be called out in the text for their match to the required topcoat-only thickness of 1.7 to 2.3 mils. In tests where the sample panels fall in different thickness ranges, the analysis will consider whether panels with a lower dry film thickness appear to be showing superior performance.

3.2. Appearance Testing

<u>Test Description</u>
These tests are fully described under Section 5.2.3.1.1 (for color) and 5.2.3.1.2 (for gloss) of this Final Report.

Color
The color readings were taken in accordance with ASTM D 2244, *Standard Practice Calculation of Color Tolerances and Color Differences from Instrumentally Measured Color Coordinates*, with three (3) tests conducted per sample panel and three panels evaluated per coating. The results were matched against a relevant color coupon from FED-STD-595C and listed as a ΔE reading from the color chip. The standard acceptance criteria for the color readings was no more than one ΔE using CIE LAB method.

Gloss

This gloss test covers the measurement of the specular gloss for glossmeter geometries of 60° and 85° in accordance with ASTM D 523, *Standard Test Method for Specular Gloss*. A glossmeter capable of reading at 60° and 85° was calibrated using a National Institute of Standards and Technology (NIST) traceable standard. The instrument was then placed on the sample, a reading was taken on three different places on the sample and an average was given. Standard acceptance criteria for the flat coatings evaluated under this effort are ≤ 5 at 60° and ≤ 9 at 85°.

<u>Results</u>

Three panels for each coating were specifically designated for color and gloss readings. The data for each panel is shown as Table 57 below.

Table 57. Gloss and Color Data

3 Trials/panel Avg. Given	Control Gray 36173	Control Black 37038	Control Gray 36173 (APC)	Deft UV Gray 36173	Deft UV Gray 36118	Deft UV Black 37038
Gloss 60 - 1	4.1	1.1	2.5	4.7	4.4	8.6
Thickness	3.5	3.5	3.3	3.4	3.9	2.8
Gloss 60 - 2	4.2	1.1	2.5	5.2	4.4	9.7
Thickness	3.7	3.3	3.0	3.2	4.1	3.0
Gloss 60 - 3	4.3	1.0	2.5	3.9	4.1	11.3
Thickness	4.0	3.2	3.2	3.6	3.8	3.2
Gloss 85 - 1	5.4	5.2	4.0	11.9	9.5	58
Thickness	***	***	***	***	***	***
Gloss 85 - 2	5.7	5.1	3.9	14.1	9.6	61.8
Thickness	***	***	***	***	***	***
Gloss 85 - 3	6.1	5.0	3.8	10.1	10.3	63
Thickness	***	***	***	***	***	***
Color ΔE - 1	0.2	1.3	0.2	0.9	10.2	0.9
Thickness	***	***	***	***	***	***
Color ΔE - 2	0.2	1.2	0.2	0.9	10.2	1.3
Thickness	***	***	***	***	***	***
Color ΔE - 3	0.2	1.2	0.2	0.8	10.1	0.6
Thickness	***	***	***	***	***	***

*** - For each coating, the same three panels were used for all color and gloss readings.

In addition to these panels specifically designated for initial gloss and color testing, readings were taken on panels to be exposed to xenon arc weathering testing at 0 hours (that is, prior to any exposure). Color and gloss weathering data is discussed in full in section 3.8, but because of the drastic difference in gloss readings between some of the 0 hour UV-curable panels and the color/gloss panels, the data is reproduced as Table 58 for comparison.

Table 58. Zero Hour Gloss and Color Data

3 Trials/panel Avg. Given	Control Gray 36173	Control Black 37038	Control Gray 36173 (APC)	Deft UV Gray 36173	Deft UV Gray 36118	Deft UV Black 37038
Gloss 60 - 1	3.8	1	2.5	4.1	3.9	5.3
Thickness	3.0	2.8	3.2	3.1	4.7	4.6
Gloss 60 - 2	3.8	1.1	2.5	3.9	4.2	5.0
Thickness	3.1	2.9	3.1	3.0	4.2	4.8
Gloss 60 - 3	3.6	1.1	2.5	4.1	4.8	4.5
Thickness	2.9	3.1	3.1	3.2	4.4	4.8
Gloss 85 - 1	4.1	4.8	3.2	9.4	8.2	12.2
Thickness	***	***	***	***	***	***
Gloss 85 - 2	4.0	4.8	2.0	10.5	8.0	11.7
Thickness	***	***	***	***	***	***
Gloss 85 - 3	3.5	4.7	3.6	10.5	8.0	11.3
Thickness	***	***	***	***	***	***

*** - For each coating, the same three panels were used for all readings

Analysis

Success/Failure Criteria: Failure by three units or less will be considered a "marginal failure" for purpose of adding nuance to the results analysis.

Coating Color: In all cases, the control coatings met specification requirements for color. Of the UV-curable coatings, the UV Gray 36173 and the UV Black 37038 met color requirements when compared to FED-STD-595 color coupons (with one slight outlier for the 37038) but were consistently further away than the control coatings. The UV Gray 36118 was far outside the color range for its FED-STD-595 coupon, showing a consistent Δ10 difference. The UV Gray 36118 will require further color matching; likely due to the speed with which it was reformulated before being sent for follow-up testing.

Coating Gloss: In all cases, the control coatings met specification requirements for gloss. The Deft UV Gray 36173 consistently met the requirement for 60° gloss, while marginally failing the 85° gloss requirement, with one outlier failing by over three units. The Deft UV Gray 36118 consistently met the requirement for 60° gloss and varied in performance against the 85° gloss requirement. The color/gloss panels for the UV Gray 36118 were consistently marginal failures, but the zero hour weathering panels for UV Gray 36118 consistently passed the 85° gloss requirement. The UV Black 37038 consistently failed 60° gloss on the color/gloss panels, and showed values situated almost exactly at the failure value of 5 for the zero hour weathering panels. The UV Black 37038 showed massive failures at 85° gloss on the color/gloss panels, with gloss readings in excess of 50. UV Black 37038 failures at 85° gloss on the zero hour weathering panels were much closer to the expected range, exceeding the requirement by less than 4.

The coating vendor Deft has advanced the theory that the gloss difference is the result of varying standards of coating application. *CTC* is proceeding with an applications engineering evaluation to evaluate the potential effects of potential application issues such as a post-cure wait period before testing or allowing applied coatings to sit under fluorescent lights before applying UV cure.

Film Thickness: Over half the panels exceeded the coating thickness required by specification by less than a mil, and many of the in-specification thickness panels were at the high end of the scale. Because color and gloss are determined by surface cure, it is not anticipated that a high dry film thickness will have a large effect on those properties.

3.3. Adhesion Testing

<u>Test Description</u>
These tests are described under Section 5.2.3.2.1 (for wet tape adhesion) and 5.2.3.2.1 (for cross hatch adhesion) of this Final Report.

Wet tape Adhesion
This test method was performed to determine the acceptability of intercoat and surface adhesion and in accordance with ASTM D 3359, Method A, Standard Test Method for Measuring Adhesion by Tape Test. Each coated specimen was soaked in distilled water for 24 hours following cure. Two parallel lines one inch apart were then scribed on the test panel. An “x” was then scribed across the two parallel lines all the way to the substrate. A piece of 3M 250 tape was placed over the incision and smoothed out before being removed rapidly. The scribed area was inspected for peel away. The standard acceptance criteria were no peel away with a target rating of 4A or 5A.

Crosshatch Adhesion
This test method was performed to determine the acceptability of intercoat and surface adhesion and in accordance with ASTM D 3359, Method B, Standard Test Method for Measuring Adhesion by Tape Test. A lattice pattern of incisions were made in the coating, scribing all the way to the substrate. A piece of 3M 250 tape was placed over the incision and smoothed out, then removed rapidly. The standard acceptance criteria were no peel away with a target rating of 4B or 5B.

<u>Results</u>
Three panels for each coating were specifically designated for wet tape and three panels were designated for crosshatch. The data for each panel is shown as Table 59 below.

Table 59. Adhesion Testing Data

1 Trial/panel	Control Gray 36173	Control Black 37038	Control Gray 36173 (APC)	Deft UV Gray 36173	Deft UV Gray 36118	Deft UV Black 37038
Wet Tape - 1	5A	5A	5A	2A	3A	3A
Thickness	***	***	***	***	***	***
Wet Tape - 2	5A	5A	5A	2A	4A	3A
Thickness	***	***	***	***	***	***
Wet Tape - 3	5A	5A	5A	1A	4A	3A
Thickness	***	***	***	***	***	***
Crosshatch - 1	4B	4B	4B	3B	4B	5B
Thickness	3.2	3.2	3.6	2.8	3.8	3.5
Crosshatch - 2	4B	4B	4B	1B	4B	5B
Thickness	3.6	3.3	3.6	3.1	4.5	3.6
Crosshatch - 3	4B	3B	4B	4B	3B	5B
Thickness	3.3	3.8	3.5	3.5	4.0	3.5

*** - Dry Film Thickness not recorded.

Analysis

Success/Failure Criteria: Failure at the level of 3A or 3B (respectively) will be considered a "marginal failure" for purpose of adding nuance to the results analysis.

Wet Tape Adhesion: In all cases, the control coatings met specification requirements for wet tape adhesion. Of the UV-curable coatings, the UV Gray 36173 consistently showed poor performance, not reaching even the "marginal failure" level of 3A in any of the three samples. The UV Gray 36118 passed for two samples and showed a marginal failure for the third. UV Black 37038 marginally failed for all three samples. Compared to the control coatings, all three UV-curable coatings showed very poor performance.

Crosshatch Adhesion: In almost all cases, the control coatings met specification requirements for cross hatch, with the exception of a marginal failure on one of the Control Black 37038 samples. Of the UV-curable coatings, the UV Gray 36173 showed inconsistent performance, with one sample passing, one sample as a marginal failure, and one sample as a complete failure. The UV Gray 36118 passed for two samples and showed a marginal failure for the third. UV Black 37038 passed fully for all three samples. Performance of the UV-curable coatings was inconsistent overall, as the three UV-curable coatings are assumed to be of extremely similar formulation with slightly differing color matching. It is uncertain why there is such variation in their performance.

Film Thickness: Over three quarters of the crosshatch panels were measured as having a coating thickness exceeding the maximum allowed by specification. Coating adhesion is an area where coating thickness is expected to strongly affect the performance of UV-curable coatings, as coatings that are of excessive thickness may prevent UV radiation from reaching all areas of the coating and achieving complete cure-through. However, no correlation between the worst-performing samples and coating thickness is visible. Of the nine UV coating cross hatch samples, those with the highest dry film thickness passed, while the two with the lowest DFT failed.

3.4. Stencil Coat Adhesion Testing

Test Description

This test is described under Section 5.2.3.2.4 of this Final Report. Due to the nature of the test, stencil coat adhesion testing was performed only for the UV-curable coatings.

This test was performed to determine the ability of UV-curable coatings to adhere to standard MIL-PRF-85285 topcoat or to an APC-qualified MIL-PRF-85285 topcoat when utilized as a stencil coating. Six panels with a topcoat meeting standard MIL-PRF-85285 and six panels with a topcoat meeting APC-qualified MIL-PRF-85285 were utilized for each UV-curable coating being tested. The most common method of surface preparation for stencil coating is light sanding, which was used for this test. After the stencil coat of UV-curable coating was applied, each sample panel was tested for wet tape and crosshatch adhesion as per sections 4.2.1 and 4.2.2 of the JTP, with standard acceptance criteria of no peel away and a target rating of 4A or 5A (for wet tape) and 4B or 5B (for crosshatch).

Results

Twelve panels for each coating were specifically designated for stencil coat adhesion testing. The data for each panel is shown as Table 60 below. Because the stencil coating adds an extra layer to the stack-up, the allowed coating range for these coatings is 4.0 to 5.5.

Table 60. Stencil Coat Adhesion Data

1 Trial/panel	Deft UV Gray 36173 on 85285	Deft UV Gray 36118 on 85285	Deft UV Black 37038 on 85285	Deft UV Gray 36173 on APC	Deft UV Gray 36118 on APC	Deft UV Black 37038 on APC
Wet Tape - 1	5A	5A	5A	5A	3A	4A
Thickness	4.3	5.0	4.8	4.6	4.7	**5.7**
Wet Tape - 2	5A	3A	5A	5A	3A	5A
Thickness	4.3	5.3	5.0	4.5	5.0	5.8
Wet Tape - 3	5A	4A	5A	5A	3A	5A
Thickness	4.6	5.4	5.2	4.8	5.4	5.8
Crosshatch - 1	4B	4B	4B	4B	0B	2B
Thickness	3.4	5.6	4.9	4.7	5.7	5.9
Crosshatch - 2	4B	3B	5B	4B	0B	1B
Thickness	3.7	5.9	4.8	4.6	5.2	5.8
Crosshatch - 3	4B	4B	4B	4B	0B	2B
Thickness	3.8	6.2	5.1	4.6	5.5	6.2

Analysis

Success/Failure Criteria: Failure at the level of 3A or 3B (respectively) will be considered a "marginal failure" for purpose of adding nuance to the results analysis.

85285 Adhesion: In most samples, the UV-curable coating successfully adhered to the standard 85285 coating. The UV Gray 36118 did show marginal failure on one wet tape and one crosshatch test.

APC Adhesion: In all samples, the UV Gray 36173 successfully adhered to the APC. The UV Gray 36118 showed a marginal failure on the APC for all wet tapes, and a complete failure on all crosshatch tests, showing a "0B" rating for every crosshatch panel. The UV Black 37038 met the wet tape requirements for adhesion to the APC, but suffered failure for all crosshatch samples on APC. Performance of the UV-curable coatings was inconsistent overall, as the three UV-curable coatings are assumed to be of extremely similar formulation with slightly differing color matching. The UV 36173 panels show a generally lower DFT for the APC samples, but the UV 37038 shows a higher DFT compared to the UV 36118, despite having a generally better performance than the 38118.

Film Thickness: A quarter of the panels demonstrated a dry film thickness exceeding the maximum allowed for a stack-up with a primer and two topcoat layers. Coating adhesion is an area where coating thickness is expected to strongly affect the performance of UV-curable coatings, as coatings that are of excessive thickness may prevent UV radiation from reaching all areas of the coating and achieving complete cure-through. However, no correlation between the worst-performing samples and coating thickness is visible.

3.5. Flexibility Testing

Test Description

These tests are described under Section 5.2.3.3.1 (for low temperature mandrel bend) and 5.2.3.3.2 (for GE Impact) of this Final Report.

Low Temperature Mandrel Bend

Low temperature flexibility is determined by use of a mandrel in accordance with ASTM D 522, Standard Test Methods for Mandrel Bend Test of Attached Organic Coatings. The specimens were brought to -60 ± 5°F for 24 hours. After completion of the exposure time, the specimens were immediately bent over the mandrel while within the test chamber to prevent change in panel and mandrel temperature. The performance requirement is no cracking or adhesion loss.

GE Impact Flexibility

Per ASTM D 6905, Standard Test Method for Impact Flexibility of Organic Coating, the GE Impact analysis procedure is used for determining the ability of a coating film and its substrate to resist shattering, cracking, or chipping when the film and the substrate are distended beyond their original form by impact. Each specimen was is placed coated side down in the testing apparatus, and a GE impact indenter was dropped from a measured height such that the full impression of the indenter was made in the panel. The panel specimen was then inspected with 10-power magnification for cracks, crazing or loss of adhesion where the impact occurred. The minimum performance requirement is that candidate coatings should exhibit no cracking, loss of adhesion, or other coating damage at 40% elongation or less.

Results

Three panels for each coating were specifically designated for low temperature mandrel bend testing and three panels were designated for GE Impact testing. The data for each panel is shown in Table 61 below. Note that as flexibility panels do not include a primer layer in the coating stack-up, the specification coating stack-up thickness is 1.7 to 2.3 mils.

Table 61. Flexibility Testing Data

1 Trial/panel	Control Gray 36173	Control Black 37038	Control Gray 36173 (APC)	Deft UV Gray 36173	Deft UV Gray 36118	Deft UV Black 37038
Low Temp - 1	Pass	Pass	Pass	Pass	Pass	Pass
Thickness	3.0	2.0	2.6	2.3	3.4	3.1
Low Temp - 2	Pass	Pass	Pass	Pass	Pass	Pass
Thickness	2.8	2.0	2.7	2.0	3.7	2.2
Low Temp - 3	Pass	Pass	Pass	Pass	Pass	Pass
Thickness	2.3	2.0	2.6	2.1	3.6	3.0
GE Impact - 1	20%	20%	20%	20%	2%	10%
Thickness	2.2	1.9	2.8	2.1	3.4	3.1
GE Impact - 2	20%	20%	10%	10%	2%	10%
Thickness	2.3	2.1	2.6	1.9	3.4	3.0
GE Impact - 3	20%	20%	10%	10%	2%	10%
Thickness	2.6	1.9	2.5	2.0	3.3	3.0

Feedback from the vendor indicated that the relatively high coating thickness of the UV-curable coating samples might be responsible for the poor GE Impact performance. A new set of panels with the UV-curable coating thickness more tightly controlled were sprayed and tested. In addition, the cured panels were allowed to sit for 14 days after cure in order to match allowed post-cure time of the control panels. The results are shown in Table 62 below.

Table 62. GE Impact Retest Data

1 Trial/panel	Deft UV Gray 36173	Deft UV Gray 36118	Deft UV Black 37038
GE Impact - 1	20%	20%	40%
Thickness	2.0	1.7	1.9
GE Impact - 2	20%	10%	40%
Thickness	2.2	1.6	1.9
GE Impact - 3	20%	10%	40%
Thickness	1.9	1.7	1.8

Analysis

Success/Failure Criteria: The requirements for cold mandrel bend will not have a “marginal fail” reading. For GE Impact, while the topcoat requirement is 40%, the primer specification requirement is only 20%. Therefore a GE Impact of 20% will be considered only a marginal failure.

Low Temperature Mandrel Bend: All coating samples passed the cold mandrel bend test

GE Impact: In the first trial, all of the control coatings resulted in a 20% marginal failure. The UV Gray 36173 and the UV Black 37038 returned results of 10% for most specimens, and the UV Gray 36118 returned extremely poor results of 2%. When tested again, the UV Gray 36118 showed a consistent 20% marginal failure result, despite a negligible difference in coating thickness. The UV Black 37038 returned a consistent passing result of 40% elongation without cracking, the only passing result from any of the GE impact testing conducted. The UV Black 37038 had a coating thickness drop of approximately 1 mil for all samples in the second round of testing. The UV Gray 36118 improved to mixed results of 20% and 10% for the three samples tested in the second round of testing, with an approximate thickness drop of one and a half mils for each sample. It seems possible that both the decreased coating thickness and the increased post-cure time played a role in improving the GE Impact performance of the UV-curable coatings. Performance of the UV-curable coatings was inconsistent overall, as the three UV-curable coatings are assumed to be of extremely similar formulation with slightly differing color matching. It is not understood at this time why the flexibility results varied so greatly between the UV-curable coating samples

Film Thickness: In the first round of GE Impact testing, eight of the nine control samples were within the specification-required coating thickness, yet none of them passed. In the second round of flexibility testing, all of the UV-curable coatings were below the specification-required maximum thickness, but only the UV Black passed. However, all three coatings showed a performance improvement as compared to the first round of flexibility testing.

3.6. Hardness Testing

<u>Test Description</u>

Pencil hardness testing is described under Section 5.2.3.4.1 of this Final Report. Pencil hardness is used to determine the hardness of an organic coating on a substrate. Testing was conducted in accordance with ASTM D 3363, Standard Test Methods for Film Hardness by Pencil Test. As testing proceeded, each pencil was held firmly against the specimen surface and pushed away from the operator in a 1/4 inch stroke. Testing started with the hardest pencil and continued down the scale of hardness until a pencil was attempted that did not scratch the film (scratch hardness). Three panels were prepared for each coating, and two pencil hardness tests were conducted on each panel, for a total of six pencil hardness readings per coating. Per feedback form end users the minimum acceptable hardness is considered to be B or harder; this data will also be used to establish an average initial hardness data point for fluid resistance evaluations.

The pencil hardness scale is: 6B < 5B < 4B< 3B< 2B< B< HB< F< H< 2H< 3H< 4H< 5H

<u>Results</u>

Three panels for each coating were specifically designated for pencil hardness, and two readings were taken for each panel. An "average" hardness reading for comparison against the fluid resistance data will be determined by plotting a medium hardness point between the six data

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points for each coating. In some cases, this part may be indicated as a range between two hardness points. The data for each panel is shown as Table 63 below.

Table 63. Hardness Testing Data

2 Trials/panel	Control Gray 36173	Control Black 37038	Control Gray 36173 (APC)	Deft UV Gray 36173	Deft UV Gray 36118	Deft UV Black 37038
Hardness - 1	3H	3H	4H	2H	H	3H
Hardness - 2	4H	3H	4H	3H	2H	2H
Thickness	2.9	3.2	3.5	3.7	4.0	2.6
Hardness - 3	3H	4H	4H	4H	H	3H
Hardness - 4	3H	4H	4H	3H	H	3H
Thickness	3.1	3.4	3.4	3.4	3.8	2.7
Hardness - 5	3H	4H	3H	2H	2H	2H
Hardness - 6	3H	4H	4H	2H	H	3H
Thickness	3.2	3.2	3.3	3.6	4.1	3.6
Average Hardness	3H	3H to 4H	4H	2H to 3H	H to 2H	2H to 3H

Analysis

Success/Failure Criteria: There is no specification-mandated initial hardness requirement, though DoD personnel at Hill Air Force Base have stated an HB or harder is desirable.

Pencil Hardness: All the control coatings seemed to fall consistently in the 3H to 4H range. All of the UV-curable coatings seemed to fall consistently into the H to 3H range.

Film Thickness: The UV-curable gray coatings were consistently applied between 0.3 and 0.9 mil thicker than allowed by the specification, though two of the UV-curable black panels were well under specification requirement.

3.7. Fluid Resistance Testing

Fluid resistance testing covers the determination of the effects of six fluids on organic finishes resulting in any objectionable alteration in the surface such as discoloration, change in gloss, blistering, softening, swelling, loss of adhesion, or other special conditions. The fluids are Mobil Jet 254 lubricating oil (conforming to MIL-PRF-23699), lubricating oil conforming to MIL-PRF-7808, hydraulic fluid conforming to MIL-PRF-83282, JP-8 fuel, deionized water, and Skydrol LD-4. Time and temperatures of exposure differ for each test, with multiple exposure times listed for some fluids to represent both minimum and optimum requirements.

After each exposure, the specimen was removed and immediately evaluated for blistering and film delamination. After the specimen was cleaned and allowed to air dry for 1-hour, the final color was measured for change from the baseline, a wet tape adhesion test was conducted, and a pencil hardness readings were taken. The averages of initial values were compared with the averages of the final values to assess compliance to the performance requirements: no peeling observed, softening of no more than two (2) pencil hardness units. As an optimum performance requirement, the coating should show a color change of $\Delta E \leq$ three (3). However, as a minimum performance requirement, slight staining of the coating is acceptable

3.7.1. Lube Oil Mobil Jet 254 - 24H at 250F

Test Description

Completely immerse panels for 24 hours @ 250±5 ºF (121±3 ºC). This is a minimum requirements test.

Results

The data for each panel is shown as Table 64 below.

Table 64. Lube Oil Mobil Jet 254 24 Hr Testing Data

	Control Gray 36173	Control Black 37038	Control Gray 36173 (APC)	Deft UV Gray 36173	Deft UV Gray 36118	Deft UV Black 37038
Color ΔE - 1	1.2	0.7	1.6	5.0	1.7	1.2
Thickness	2.8	2.8	3.9	3.0	4.5	3.0
Color ΔE - 2	1.1	3.9	1.8	4.6	1.6	6.1
Thickness	3.5	2.7	3.5	3.0	4.7	2.8
Color ΔE - 3	2.5	0.8	1.2	4.2	1.6	0.9
Thickness	2.9	2.3	3.3	3.0	4.6	2.6
Wet Tape - 1	5A	5A	5A	5A	5A	5A
Thickness	***	***	***	***	***	***
Wet Tape - 2	5A	5A	5A	5A	5A	5A
Thickness	***	***	***	***	***	***
Wet Tape - 3	5A	5A	5A	5A	5A	5A
Thickness	***	***	***	***	***	***
Hardness - 1	4H	3H	5H	F	F	F
Hardness - 2	3H	3H	5H	F	F	H
Thickness	***	***	***	***	***	***
Hardness - 3	3H	2H	5H	F	HB	H
Hardness - 4	4H	2H	5H	F	F	H
Thickness	***	***	***	***	***	***
Hardness - 5	3H	3H	4H	F	B	H
Hardness - 6	4H	2H	4H	H	B	H
Thickness	***	***	***	***	***	***
Average Hardness	3H to 4H	2H to 3H	4H to 5H	F	HB	H
Presoak Avg. Hardness	3H	3H to 4H	4H	2H to 3H	H to 2H	2H to 3H

*** - For each coating, the same three panels were used for all color, adhesion, and hardness readings.

Analysis:

Success/Failure Criteria: The success criteria are a ΔE color change of ≤3 and a pencil hardness change of ≤2. If the color change exceeds the allowed delta by less than one, it will be considered a marginal optimum performance failure. If the post-exposure hardness softens by between two and three units, it will be considered a marginal failure.

Color Change: Only one of the control samples exceeded the allowed color change, and it was a marginal failure. Of the UV-curable samples, the UV 36173 Gray consistently exceeded the allowed color change, UV Gray 36118 consistently met the requirement, and the UV Black

37038 met the requirements with two samples and had a serious failure with the third. There is no explanation of why performance of the UV-curable samples demonstrates such high variation.

Wet Tape Adhesion: For all samples, despite receiving a passing score the tester noted that the tape adhered poorly to treated test surface and the results may therefore not be fully reliable.

Pencil Hardness: The control panels all passed the pencil hardness requirement, showing little to no drop in pencil hardness post-exposure. The UV-curable gray coatings were marginal failures with a pencil hardness change of approximately two and a half, and the UV Black 37038 was what might be called a marginal success, with a pencil hardness change of approximately one and a half. It is notable that the UV Gray 36118 samples, which showed hardness values lower than that of any other coatings, all three samples showed coating stack-up thicknesses more than a mil above the recommended values. This suggests the reduced hardness may be due to coating thickness (but see other fluid resistance testing data).

Film Thickness: Only the UV Gray 36118 samples showed a dry film thickness significantly above the recommended values.

3.7.2. Lube Oil MIL-PRF-7808 - 24H at 250F

Test Description
Completely immerse panels for 24 hours @ 250±5 ºF (121±3 ºC). This is a minimum requirements test.

Results
The data for each panel is shown as Table 65 below.

Table 65. Lube Oil MIL-PRF-7808 24 Hr Testing Data

	Control Gray 36173	Control Black 37038	Control Gray 36173 (APC)	Deft UV Gray 36173	Deft UV Gray 36118	Deft UV Black 37038
Color ΔE - 1	1.0	0.4	1.1	4.9	2.6	1.4
Thickness	3.9	3.2	3.0	3.3	4.5	3.7
Color ΔE - 2	0.9	0.7	1.1	4.8	2.3	1.1
Thickness	4.0	3.3	3.0	3.2	4.7	3.6
Color ΔE - 3	1.1	0.4	1.1	4.9	2.5	1.3
Thickness	3.7	3.1	3.2	3.2	4.3	3.7
Wet Tape - 1	4A	4A	4A	4A	3A	4A
Thickness	***	***	***	***	***	***
Wet Tape - 2	4A	4A	4A	4A	2A	3A
Thickness	***	***	***	***	***	***
Wet Tape - 3	4A	4A	4A	4A	4A	1A
Thickness	***	***	***	***	***	***
Hardness - 1	5H	4H	5H	B	2B	B
Hardness - 2	5H	4H	5H	B	2B	B
Thickness	***	***	***	***	***	***
Hardness - 3	5H	5H	5H	B	B	B
Hardness - 4	5H	5H	5H	B	B	HB
Thickness	***	***	***	***	***	***
Hardness - 5	5H	4H	4H	B	B	HB
Hardness - 6	5H	5H	5H	B	B	HB
Thickness	***	***	***	***	***	***
Average Hardness	5H	4H to 5H	5H	B	2B to B	B to HB
Presoak Avg. Hardness	3H	3H to 4H	4H	2H to 3H	H to 2H	2H to 3H

*** - For each coating, the same three panels were used for all color, adhesion, and hardness readings.

Analysis:

Success/Failure Criteria: The success criteria are a ΔE color change of ≤3 and a pencil hardness change of ≤2. If the color change exceeds the allowed delta by less than one, it will be considered a marginal optimum performance failure. If the post-exposure hardness softens by between two and three units, it will be considered a marginal failure.

Color Change: All of the control samples met the allowed color change performance criteria. Of the UV-curable samples, the UV 36173 Gray consistently exceeded the allowed color change, UV Gray 36118 and the UV Black 37038 consistently met the requirement. This is consistent with the previous lube oil data for color changes, in which the UV Gray 36173 also showed the most color change from exposure.

Wet Tape Adhesion: For the Control Gray 37038, the UV Gray 36118, and the UV Black 37038, the tester noted that the tape adhered poorly to treated test surface and the results may therefore not be fully reliable. Wet tape adhesion failures were noted for the UV Gray 36118 and the UV Black 37038, which had notably higher dry film thickness readings than the UV Gray 37038.

Pencil Hardness: The control panels all passed the pencil hardness requirement, showing little to no drop in pencil hardness post-exposure. The UV-curable coatings were failures of more than three pencil hardness. Consistently low pencil hardness values were found for all of the UV-curable coatings, including the UV Gray 36173, which had a dry film thickness within specification for all samples.

Film Thickness: Only the UV Gray 36118 samples showed a dry film thickness significantly above the recommended values, with the UV 37038 exceeding recommended dry film thickness values by less than a mil.

3.7.3. Hydraulic Fluid MIL-PRF-83282 - 24H at 250F

<u>Test Description</u>
Completely immerse panels for 24 hours @ 250±5 ºF (121±3 ºC). This is a minimum requirements test.

<u>Results</u>
The data for each panel is shown as Table 66 below.

Table 66. Hydraulic Fluid MIL-PRF-83282 24 Hr Testing Data

	Control Gray 36173	Control Black 37038	Control Gray 36173 (APC)	Deft UV Gray 36173	Deft UV Gray 36118	Deft UV Black 37038
Color ΔE - 1	0.4	0.4	0.7	1.5	1.9	0.3
Thickness	3.1	3.5	3.3	3.1	4.5	3.5
Color ΔE - 2	0.6	0.5	0.5	1.5	1.9	0.8
Thickness	3.1	3.3	3.6	2.9	3.8	3.4
Color ΔE - 3	0.6	0.4	0.6	1.4	1.9	1.3
Thickness	3.0	3.1	3.3	3.3	4.5	2.9
Wet Tape - 1	4A	4A	4A	4A	5A	5A
Thickness	***	***	***	***	***	***
Wet Tape - 2	4A	4A	4A	4A	5A	5A
Thickness	***	***	***	***	***	***
Wet Tape - 3	4A	4A	4A	4A	5A	5A
Thickness	***	***	***	***	***	***
Hardness - 1	5H	5H	5H	F	HB	F
Hardness - 2	5H	5H	5H	F	F	F
Thickness	***	***	***	***	***	***
Hardness - 3	5H	5H	5H	F	F	F
Hardness - 4	5H	4H	4H	F	HB	F
Thickness	***	***	***	***	***	***
Hardness - 5	5H	5H	5H	F	F	H
Hardness - 6	5H	5H	5H	F	HB	H
Thickness	***	***	***	***	***	***
Average Hardness	5H	5H	5H	F	HB to F	F to H
Presoak Avg. Hardness	3H	3H to 4H	4H	2H to 3H	H to 2H	2H to 3H

*** - For each coating, the same three panels were used for all color, adhesion, and hardness readings.

<u>Analysis</u>:

Success/Failure Criteria: The success criteria are a ΔE color change of ≤3 and a pencil hardness change of ≤2. If the color change exceeds the allowed delta by less than one, it will be considered a marginal optimum performance failure. If the post-exposure hardness softens by between two and three units, it will be considered a marginal failure.

Color Change: All of the coating samples met the allowed color change performance criteria, with the control coatings showing very little color change. It does not appear that hydraulic fluid impacts coating color to a great extent.

Wet Tape Adhesion: All of the coating samples passed wet tape adhesion.

Pencil Hardness: The control panels all passed the pencil hardness requirement, showing little to no drop in pencil hardness post-exposure. The UV Gray 36173 was a marginal failure, with a failure of slightly above two units softening. The UV Gray 36118 and UV Black 37038 were marginal successes, softening exactly two units each. Because of the inherent subjectivity in pencil hardness tests, all UV-curable coatings can be considered to have softened an approximately equal amount.

Film Thickness: Many of the samples were in the slight overspray area for dry film thickness, exceeding the recommended thickness by less than a mil. The UV Gray 36118 had two samples exceeding recommended thickness by well over a mil and showed the lowest pencil hardness readings of any of the samples.

3.7.4. Lube Oil MIL-PRF-7808 – 7 Days at 250F

<u>Test Description</u>
Completely immerse panels for 7 days @ 250±5 ºF (121±3 ºC). This is an optimum requirements test.

<u>Results</u>
The data for each panel is shown as Table 67 below.

Table 67. Lube Oil MIL-PRF-7808 7 days Testing Data

	Control Gray 36173	Control Black 37038	Control Gray 36173 (APC)	Deft UV Gray 36173	Deft UV Gray 36118	Deft UV Black 37038
Color ΔE - 1	1.1	0.7	0.8	2.3	0.7	1.2
Thickness	2.7	2.9	3.0	2.8	4.0	2.7
Color ΔE - 2	0.6	0.8	0.4	2.4	0.6	1.1
Thickness	3.0	2.8	3.9	3.1	3.6	2.6
Color ΔE - 3	0.7	0.5	0.6	2.3	0.6	1.3
Thickness	2.9	3.3	3.6	3.1	4.4	2.6
Wet Tape - 1	5A	5A	5A	5A	5A	5A
Thickness	***	***	***	***	***	***
Wet Tape - 2	5A	5A	5A	5A	5A	5A
Thickness	***	***	***	***	***	***
Wet Tape - 3	5A	4A	4A	5A	5A	5A
Thickness	***	***	***	***	***	***
Hardness - 1	5H	5H	5H	H	F	H
Hardness - 2	5H	5H	5H	H	F	H
Thickness	***	***	***	***	***	***
Hardness - 3	5H	5H	5H	H	F	H
Hardness - 4	5H	5H	5H	H	F	H
Thickness	***	***	***	***	***	***
Hardness - 5	5H	5H	5H	F	F	H
Hardness - 6	5H	5H	5H	F	H	H
Thickness	***	***	***	***	***	***
Average Hardness	5H	5H	5H	F to H	F	H
Presoak Avg. Hardness	3H	3H to 4H	4H	2H to 3H	H to 2H	2H to 3H

*** - For each coating, the same three panels were used for all color, adhesion, and hardness readings.

Analysis:

Success/Failure Criteria: The success criteria are a ΔE color change of ≤3 and a pencil hardness change of ≤2. If the color change exceeds the allowed delta by less than one, it will be considered a marginal optimum performance failure. If the post-exposure hardness softens by between two and three units, it will be considered a marginal failure.

Color Change: All of the coating samples met the allowed color change performance criteria, with the control coatings showing very little color change. In the 24 Hr Lube Oil test the UV Gray 36173 experienced a much greater color change despite a shorter exposure. Though the

UV Gray 36173 experienced a smaller color change in this test, it still showed the greatest color change of any of the coatings.

Wet Tape Adhesion: All of the coating samples passed wet tape adhesion.

Pencil Hardness: The control panels all passed the pencil hardness requirement, showing little to no drop in pencil hardness post-exposure. The UV-curable coatings all passed, but all of them showed a drop in pencil hardness. The pencil hardness data is inconsistent with the 24 HR 7808 Lube Oil exposure, which resulted in pencil hardness readings of HB or worse for all UV-curable coatings. In this test, none of the UV-curable coatings showed a pencil hardness worse than F. Even the UV 36173, which showed consistent dry film thickness readings between both tests, showed radically different pencil hardness readings.

Film Thickness: Some of the samples were in the slight overspray area for dry film thickness, exceeding the recommended thickness by less than a mil. All of the UV Gray 36118 samples exceeded recommended thickness, one doing so by over a mil.

3.7.5. Jet Fuel JP-8 – 7 Days at 77F

<u>Test Description</u>
Completely immerse one set of three test panels for Seven (7) days @ 77±5 ºF (25±3 ºC). This is a minimum requirements test.

<u>Results</u>
The data for each panel is shown as Table 68 below.

Table 68. Jet Fuel JP-8 7 days Testing Data

	Control Gray 36173	Control Black 37038	Control Gray 36173 (APC)	Deft UV Gray 36173	Deft UV Gray 36118	Deft UV Black 37038
Color ΔE - 1	0.1	0.1	0.1	0.5	0.4	0.3
Thickness	4.1	2.9	3.4	2.6	4.9	2.7
Color ΔE - 2	0.1	0.1	0.1	0.5	0.3	0.4
Thickness	4.2	3.2	4.0	2.5	**5.3**	2.9
Color ΔE - 3	0.2	0.1	0.1	0.5	0.3	0.7
Thickness	3.4	3.3	3.3	2.7	4.6	2.7
Wet Tape - 1	4A	4A	4A	2A	4A	4A
Thickness	***	***	***	***	***	***
Wet Tape - 2	4A	4A	4A	2A	3A	4A
Thickness	***	***	***	***	***	***
Wet Tape - 3	4A	4A	3A	1A	3A	4A
Thickness	***	***	***	***	***	***
Hardness - 1	5H	4H	5H	2B	2B	F
Hardness - 2	5H	4H	5H	2B	2B	F
Thickness	***	***	***	***	***	***
Hardness - 3	5H	4H	5H	3B	3B	H
Hardness - 4	5H	4H	5H	3B	3B	H
Thickness	***	***	***	***	***	***
Hardness - 5	5H	4H	5H	3B	3B	F
Hardness - 6	5H	5H	5H	4B	3B	H
Thickness	***	***	***	***	***	***
Average Hardness	5H	4H	5H	3B	3B to 2B	F to H
Presoak Avg. Hardness	3H	3H to 4H	4H	2H to 3H	H to 2H	2H to 3H

*** - For each coating, the same three panels were used for all color, adhesion, and hardness readings.

Analysis:
Success/Failure Criteria: The success criteria are a ΔE color change of ≤3 and a pencil hardness change of ≤2. If the color change exceeds the allowed delta by less than one, it will be considered a marginal optimum performance failure. If the post-exposure hardness softens by between two and three units, it will be considered a marginal failure.

Color Change: All of the coating samples met the allowed color change performance criteria, with the control coatings showing very little color change. The UV-curable coating samples all showed a delta color change of less than 1.

Wet Tape Adhesion: All of the control coating samples passed wet tape adhesion. The UV Gray 36173 and the UV Gray 36118 both experienced failures in wet tape adhesion, while the UV Black 37038 passed wet tape adhesion.

Pencil Hardness: The control panels all passed the pencil hardness requirement, showing little to no drop in pencil hardness post-exposure. The UV Gray 36173 and the UV Gray 36118 both experienced catastrophic coating softening, dropping to values of 2B and below. The UV Gray 36173 samples were all applied at a dry film thickness well within specification, while the UV Gray 36118 samples were over a mil (and in one case over two mils) beyond the recommended DFT. Yet both gray coatings showed an equivalent poor performance in pencil hardness, suggesting that coating thickness was not the primary issue. The UV Black 37038 passed pencil hardness tests.

Film Thickness: Seven of the nine control samples were applied at slightly over the recommended thickness. The UV Gray 36173 and UV Black 37038 samples were all applied at a dry film thickness well within specification, while the UV Gray 36118 samples were over a mil (and in one case over two mils) beyond the recommended DFT.

3.7.6. Jet Fuel JP-8 – 30 Days at 77F

<u>Test Description</u>
Completely immerse one set of three test panels for thirty (30) days @ 77±5 ºF (25±3 ºC). This is an optimum performance requirements test.

<u>Results</u>
The data for each panel is shown as Table 69 below.

Table 69. Jet Fuel JP-8 30 days Testing Data

	Control Gray 36173	Control Black 37038	Control Gray 36173 (APC)	Deft UV Gray 36173	Deft UV Gray 36118	Deft UV Black 37038
Color ΔE - 1	0.2	0.1	0.2	0.7	0.4	0.9
Thickness	3.1	3.3	3.5	2.7	4.5	2.8
Color ΔE - 2	0.2	0.1	0.1	0.8	0.4	1.0
Thickness	2.9	3.0	4.1	2.5	4.8	3.0
Color ΔE - 3	0.2	0.1	0.1	0.9	0.4	1.0
Thickness	2.9	3.0	4.3	2.5	4.5	3.0
Wet Tape - 1	4A	4A	4A	0A	4A	4A
Thickness	***	***	***	***	***	***
Wet Tape - 2	4A	4A	4A	2A	4A	4A
Thickness	***	***	***	***	***	***
Wet Tape - 3	4A	4A	4A	3A	4A	4A
Thickness	***	***	***	***	***	***
Hardness - 1	3H	3H	4H	<5B	3B	B
Hardness - 2	3H	3H	4H	4B	2B	B
Thickness	***	***	***	***	***	***
Hardness - 3	3H	3H	4H	3B	3B	B
Hardness - 4	3H	2H	4H	3B	3B	B
Thickness	***	***	***	***	***	***
Hardness - 5	3H	2H	4H	3B	3B	B
Hardness - 6	3H	2H	4H	3B	2B	B
Thickness	***	***	***	***	***	***
Average Hardness	3H	2H to 3H	4H	4B to 3B	3B to 2B	B
Presoak Avg. Hardness	3H	3H to 4H	4H	2H to 3H	H to 2H	2H to 3H

*** - For each coating, the same three panels were used for all color, adhesion, and hardness readings.

<u>Analysis</u>:
Success/Failure Criteria: The success criteria are a ΔE color change of ≤3 and a pencil hardness change of ≤2. If the color change exceeds the allowed delta by less than one, it will be considered a marginal optimum performance failure. If the post-exposure hardness softens by between two and three units, it will be considered a marginal failure.

Color Change: All of the coating samples met the allowed color change performance criteria, with the control coatings showing very little color change. The UV-curable coating samples all showed a delta color change of 1 or less.

Wet Tape Adhesion: All of the control coating samples passed wet tape adhesion. The UV Gray 36173 experienced failures in wet tape adhesion, while the UV Black 37038 and the UV Gray 36118 both passed wet tape adhesion.

Pencil Hardness: The control panels all passed the pencil hardness requirement, showing little to no drop in pencil hardness post-exposure. The UV Gray 36173 and the UV Gray 36118 both experienced catastrophic coating softening, dropping to values of 2B and below. The UV Gray 36173 samples were all applied at a dry film thickness well within specification, while the UV Gray 36118 samples were over a mil beyond the recommended DFT. Yet both gray coatings showed an equivalent poor performance in pencil hardness, suggesting that coating thickness was not the primary issue. The UV Black 37038 suffered a serious loss in pencil hardness to a consistent pencil hardness of B, which is also a failure compared to its initial value of over 2H.

Film Thickness: Three of the nine control samples were applied at slightly over the recommended thickness. The UV Gray 36173 and UV Black 37038 samples were all applied at a dry film thickness well within specification, while the UV Gray 36118 samples were over a mil beyond the recommended DFT.

3.7.7. Deionized Water – 30 Days at 120F

Test Description

Completely immerse one set of three test panels for thirty (30) days @ 120±5 ºF (49±3 ºC). This is an optimum performance requirements test.

Results

The data for each panel is shown as Table 70 below.

Table 70. Deionized Water 30 days Testing Data

	Control Gray 36173	Control Black 37038	Control Gray 36173 (APC)	Deft UV Gray 36173	Deft UV Gray 36118	Deft UV Black 37038
Color ΔE - 1	0.8	0.8	1.2	2.0	1.6	2.9
Thickness	2.9	3.3	3.6	2.5	4.6	3.0
Color ΔE - 2	0.9	0.5	0.8	2.0	1.7	2.9
Thickness	2.9	3.1	3.7	2.8	4.4	3.3
Color ΔE - 3	0.8	0.8	0.5	2.0	1.5	2.7
Thickness	3.0	3.0	3.7	2.6	4.1	3.2
Wet Tape - 1	4A	4A	4A	0A	0A	1A
Thickness	***	***	***	***	***	***
Wet Tape - 2	4A	4A	4A	0A	0A	0A
Thickness	***	***	***	***	***	***
Wet Tape - 3	4A	4A	4A	0A	0A	0A
Thickness	***	***	***	***	***	***
Hardness - 1	2H	2H	2H	<5B	<5B	F
Hardness - 2	2H	2H	2H	<5B	<5B	F
Thickness	***	***	***	***	***	***
Hardness - 3	2H	2H	2H	<5B	<5B	F
Hardness - 4	2H	2H	2H	<5B	<5B	H
Thickness	***	***	***	***	***	***
Hardness - 5	2H	2H	2H	<5B	<5B	F
Hardness - 6	2H	2H	2H	<5B	<5B	F
Thickness	***	***	***	***	***	***
Average Hardness	2H	2H	2H	<5B	<5B	F
Presoak Avg. Hardness	3H	3H to 4H	4H	2H to 3H	H to 2H	2H to 3H

*** - For each coating, the same three panels were used for all color, adhesion, and hardness readings.

Analysis:

Success/Failure Criteria: The success criteria are a ΔE color change of ≤3 and a pencil hardness change of ≤2. If the color change exceeds the allowed delta by less than one, it will be considered a marginal optimum performance failure. If the post-exposure hardness softens by between two and three units, it will be considered a marginal failure.

Color Change: All of the coating samples met the allowed color change performance criteria, with the control coatings showing less color change than the UV-curable coating samples.

Wet Tape Adhesion: All of the control coating samples passed wet tape adhesion. All the UV-curable coatings failed wet tape adhesion, with near-complete peel-away in almost all cases.

Pencil Hardness: The control panels all passed the pencil hardness requirement, though all showed a drop in pencil hardness post-exposure. The UV Gray 36173 and the UV Gray 36118 both experienced catastrophic coating softening, dropping to values of less than 5B (too soft to measure) in all cases. The UV Gray 36173 samples were all applied at a dry film thickness well within specification, while the UV Gray 36118 samples were over a mil beyond the recommended DFT. Yet both gray coatings showed an equivalent poor performance in pencil hardness, suggesting that coating thickness was not the primary issue. The UV Black 37038 suffered a marginal failure in pencil hardness by dropping to a consistent pencil hardness of F, failing by less than 3 pencil hardness units .

Film Thickness: Four of the nine control samples were applied at slightly over the recommended thickness. The UV Gray 36173 and UV Black 37038 samples were all applied at a dry film thickness at or very close to being within specification, while the UV Gray 36118 samples were over a mil beyond the recommended DFT in two of three cases.

3.7.8. Skydrol (unscribed) – 30 Days at 77F

Test Description

Using Skydrol LD-4 at 77±5 ºF (25±3 ºC), three panels for each coating were wetted once each day (no immersion) for 30 days. This is an optimum performance requirements test.

Results

The data for each panel is shown as Table 71 below.

Table 71. Skydrol (unscribed) 30 days Testing Data

	Control Gray 36173	Control Black 37038	Control Gray 36173 (APC)	Deft UV Gray 36173	Deft UV Gray 36118	Deft UV Black 37038
Color ΔE - 1	0.5	0.7	0.4	Panels could not be evaluated: The topcoat was completely stripped off of the substrate. Topcoat seemed to swell and sag within 10 days of testing; after 30 days, adhesion was completely lost and coating was bound to panel	1.4	2.7
Thickness	2.8	3.2	3.7		4.1	3.3
Color ΔE - 2	0.4	0.4	0.4		1.3	2.9
Thickness	2.8	3.1	3.6		4.7	3.2
Color ΔE - 3	0.5	0.6	0.4		1.3	2.8
Thickness	2.7	2.9	3.4		4.9	3.4
Wet Tape - 1	4A	4A	4A		4A	4A
Thickness	***	***	***		***	***
Wet Tape - 2	4A	4A	4A		4A	4A
Thickness	***	***	***		***	***
Wet Tape - 3	4A	4A	4A		4A	4A
Thickness	***	***	***		***	***
Hardness - 1	2B	2B	2B		<5B	<5B
Hardness - 2	2B	2B	2B		<5B	<5B
Thickness	***	***	***		***	***
Hardness - 3	2B	2B	2B		<5B	<5B
Hardness - 4	2B	2B	2B		<5B	<5B
Thickness	***	***	***		***	***
Hardness - 5	2B	2B	2B		<5B	<5B
Hardness - 6	2B	2B	2B		<5B	<5B
Thickness	***	***	***		***	***
Average Hardness	2B	2B	2B		<5B	<5B
Presoak Avg. Hardness	3H	3H to 4H	4H	2H to 3H	H to 2H	2H to 3H

*** - For each coating, the same three panels were used for all color, adhesion, and hardness readings.

Analysis:
Success/Failure Criteria: The success criteria are a ΔE color change of ≤3 and a pencil hardness change of ≤2. If the color change exceeds the allowed delta by less than one, it will be considered a marginal optimum performance failure. If the post-exposure hardness softens by between two and three units, it will be considered a marginal failure.

Color Change: All of the measurable coating samples met the allowed color change performance criteria. The UV Gray 36173 was not measurable due to complete coating adhesion failure.

Wet Tape Adhesion: All of the measurable coating samples passed wet tape adhesion. For the measurable UV-curable samples, the tester noted the tape as having adhered poorly to the coating surface, meaning the results may not be reliable. The UV Gray 36173 was not measurable due to complete coating adhesion failure.

Pencil Hardness: All the sample panels failed the pencil hardness requirement, with the control coatings falling to a consistent softness of 2B. The UV Gray 36118 and UV Black 37038 both experienced catastrophic coating softening, dropping to values of less than 5B (too soft to measure) in all cases. The UV Black 37038 samples were all applied at a dry film thickness slightly over specification, while the UV Gray 36118 samples were over a mil beyond the recommended DFT. Yet both coatings showed an equivalent poor performance in pencil hardness, suggesting that coating thickness was not the primary issue. The UV Gray 36173 was not measurable due to complete coating adhesion failure.

Film Thickness: Three of the nine control samples were applied at slightly over the recommended thickness. The UV Black 37038 samples were all applied at a dry film thickness at or very close to being within specification, while the UV Gray 36118 samples were over a mil beyond the recommended DFT in two of three cases.

3.7.9. Skydrol (scribed) – 30 Days at 77F

Test Description

Scribe three additional panels for each coating with a 4± 0.125 inch diagonal line. Using Skydrol LD-4 at 77±5 ºF (25±3 ºC), three panels for each coating were wetted once each day (no immersion) for 30 days. This is an optimum performance requirements test.

Results

The data for each panel is shown as Table 72 below.

Table 72. Skydrol (scribed) 30 days Testing Data

	Control Gray 36173	Control Black 37038	Control Gray 36173 (APC)	Deft UV Gray 36173	Deft UV Gray 36118	Deft UV Black 37038
Thickness - 1	2.9	3.0	3.6	3.1	4.3	3.2
Thickness - 2	3.0	3.3	3.6	3.1	**5.5**	2.6
Thickness - 3	2.9	2.9	3.6	3.1	4.6	2.7
Visual Inspection	No apparent visual damage.	No apparent visual damage.	No apparent visual damage.	Coating blistered severely around scribe within 24 hours. Complete separation from primer layer within 2 weeks.	Small blisters formed around edges of panel.	Small blisters formed around some panel edges.

Analysis:
Success/Failure Criteria: Visual inspection should show no apparent damage or peeling.

Visual Inspection: Performance was similar to the unscribed panels. No blistering or peel-away occurred with the controls. Complete coating separation occurred with the Deft UV Gray 36173. The Deft UV Gray 36118 and Deft UV Gray 36038 each suffered some blistering but no coating peel-away.

Film Thickness: Four of the nine control samples were applied at slightly over the recommended thickness. The UV Gray 36173 and UV Black 37038 samples were all applied at a dry film thickness within specification, while the UV Gray 36118 samples were two mils or more beyond the recommended DFT in all three samples.

3.8. Accelerated Weathering (Color and Gloss)

Test Description
This test is described under Section 5.2.3.4.3 of this Final Report. This test determines the ability of a coated sample to withstand accelerated weathering in a weatherometer chamber when tested in accordance with ASTM G 155, Standard Practice for Operating Xenon Arc Light Apparatus for Exposure of Non-Metallic Materials. Three performance samples of each type were exposed for 3,000 hours with color and gloss differences checked every 500 hours as per

methodologies previously specified. Color and gloss measurements at 500 hour represent the minimum performance requirement, and color and gloss at 3,000 hours represent the optimum performance requirement.

Results

Three panels for each coating were specifically designated for accelerated weathering color and gloss readings. The 60° gloss, 85° gloss, and color data for each panel is shown as Table 73, 74, and 75 below.

Table 73. Accelerated Weathering 60° Gloss Data

3 Trials/panel Avg. Given	Control Gray 36173	Control Black 37038	Control Gray 36173 (APC)	Deft UV Gray 36173	Deft UV Gray 36118	Deft UV Black 37038
Gloss 60 – 1 (0 hours)	3.8	1.0	2.5	4.1	3.9	5.3
Thickness	3.0	2.8	3.2	3.1	4.7	4.6
Gloss 60 – 1 (500 hours)	*	1.0	2.6	1.3	2.3	1.4
Gloss 60 – 1 (1000 hours)	3.2	1.4	2.4	1.2	1.5	0.9
Gloss 60 – 1 (1500 hours)	3.0	1.7	2.3	1.1	1.3	0.7
Gloss 60 – 1 (2000 hours)	2.7	1.6	2.2	1.1	1.1	0.4
Gloss 60 – 1 (2500 hours)	2.6	1.5	2.2	1.1	1.0	0.4
Gloss 60 – 1 (3000 hours)	2.2	1.1	2.2	1.1	0.8	0.3
Gloss 60 – 2 (0 hours)	3.8	1.1	2.5	3.9	4.2	5.0
Thickness	3.1	2.9	3.1	3.0	4.2	4.8
Gloss 60 – 2 (500 hours)	*	1.0	2.6	1.6	2.2	1.9
Gloss 60 – 2 (1000 hours)	3.2	1.6	2.4	1.3	1.6	1.0
Gloss 60 – 2 (1500 hours)	3.0	1.8	2.3	1.2	1.4	0.8
Gloss 60 – 2 (2000 hours)	2.8	1.6	2.2	1.2	1.1	0.5
Gloss 60 – 2 (2500 hours)	2.6	1.7	2.3	1.2	1.0	0.4
Gloss 60 – 2 (3000 hours)	2.4	1.3	2.2	1.2	0.8	0.3
Gloss 60 – 3 (0 hours)	3.6	1.1	2.5	4.1	4.8	4.5
Thickness	2.9	3.1	3.1	3.2	4.4	4.8
Gloss 60 – 3 (500 hours)	*	1.1	2.5	1.7	2.5	1.7
Gloss 60 – 3 (1000 hours)	3.1	1.7	2.3	1.4	1.7	1.0
Gloss 60 – 3 (1500 hours)	2.9	1.8	2.3	1.2	1.5	0.7
Gloss 60 – 3 (2000 hours)	2.7	1.7	2.2	1.2	1.2	0.5
Gloss 60 – 3 (2500 hours)	2.5	1.6	2.3	1.1	1.0	0.6
Gloss 60 – 3 (2000 hours)	2.2	1.2	2.2	1.1	0.8	0.3

*Gloss readings lost after panel returned to weathering chamber

Table 74. Accelerated Weathering 85° Gloss Data

3 Trials/panel Avg. Given	Control Gray 36173	Control Black 37038	Control Gray 36173 (APC)	Deft UV Gray 36173	Deft UV Gray 36118	Deft UV Black 37038
Gloss 85 – 1 (0 hours)	4.1	4.8	3.2	9.4	8.2	12.2
Thickness	3.0	2.8	3.2	3.1	4.7	4.6
Gloss 85 – 1 (500 hours)	*	6.2	3.3	4.7	7.7	7.0
Gloss 85 – 1 (1000 hours)	6.4	9.2	3.3	10.0	9.6	7.1
Gloss 85 – 1 (1500 hours)	7.4	11.9	3.5	14.1	10.6	7.8
Gloss 85 – 1 (2000 hours)	8.5	12.7	3.4	15.3	12.7	7.6
Gloss 85 – 1 (2500 hours)	8.5	11.7	3.1	13.8	11.1	6.6
Gloss 85 – 1 (3000 hours)	9.2	11.5	3.2	11.2	11.1	8.2
Gloss 85 – 2 (0 hours)	4.0	4.8	3.0	10.5	8.0	11.7
Thickness	3.1	2.9	3.1	3.0	4.2	4.8
Gloss 85 – 2 (500 hours)	*	5.9	3.5	5.5	7.3	8.3
Gloss 85 – 2 (1000 hours)	6.0	9.3	3.6	12.1	8.3	10.0
Gloss 85 – 2 (1500 hours)	7.1	12.7	3.6	18.3	10.3	10.7
Gloss 85 – 2 (2000 hours)	8.0	12.7	3.6	19.0	9.6	12.8
Gloss 85 – 2 (2500 hours)	8.0	12.3	3.4	18.2	10.0	10.0
Gloss 85 – 2 (3000 hours)	8.7	12.8	3.4	18.8	8.9	11.5
Gloss 85 – 3 (0 hours)	3.5	4.7	2.6	10.5	8.0	11.5
Thickness	2.9	3.1	3.1	3.2	4.4	4.8
Gloss 85 – 3 (500 hours)	*	6.1	2.7	5.5	7.2	8.3
Gloss 85 – 3 (1000 hours)	5.4	9.6	2.8	15.1	9.1	8.4
Gloss 85 – 3 (1500 hours)	6.3	11.7	2.7	17.5	12.2	9.4
Gloss 85 – 3 (2000 hours)	7.4	12.8	2.8	19.0	12.4	10.1
Gloss 85 – 3 (2500 hours)	7.5	12.4	2.6	18.0	11.6	13.5
Gloss 85 – 3 (3000 hours)	8.1	12.0	2.6	19.0	11.0	11.6

*Gloss readings lost after panel returned to weathering chamber

Table 75. Accelerated Weathering Color Data

3 Trials/panel Avg. Given	Control Gray 36173	Control Black 37038	Control Gray 36173 (APC)	Deft UV Gray 36173	Deft UV Gray 36118	Deft UV Black 37038
Thickness	3.0	2.8	3.2	3.1	4.7	4.6
Color ΔE – 1 (500 hours)	**0.7**	**0.7**	**0.1**	**1.0**	**0.5**	**1.3**
Color ΔE – 1 (1000 hours)	1.5	1.7	0.1	9.1	4.4	1.2
Color ΔE – 1 (1500 hours)	1.9	2.1	0.2	9.3	7.7	0.7
Color ΔE – 1 (2000 hours)	2.4	1.5	0.2	10.0	9.9	1.1
Color ΔE – 1 (2500 hours)	2.9	1.2	0.2	10.6	11.1	1.6
Color ΔE – 1 (3000 hours)	3.9	0.8	0.2	11.3	12.4	2.2
Thickness	3.1	2.9	3.1	3.0	4.2	4.8
Color ΔE – 2 (500 hours)	0.7	0.6	0.1	0.9	0.6	1.1
Color ΔE – 2 (1000 hours)	1.4	1.5	0.2	9.8	5.0	0.8
Color ΔE – 2 (1500 hours)	1.8	1.5	0.2	9.3	8.2	1.1
Color ΔE – 2 (2000 hours)	2.3	1.4	0.2	9.9	10.1	0.9
Color ΔE – 2 (2500 hours)	2.7	1.3	0.2	10.8	11.3	1.5
Color ΔE – 2 (3000 hours)	3.7	1.1	0.2	11.2	12.4	2.0
Thickness	2.9	3.1	3.1	3.2	4.4	4.8
Color ΔE – 3 (500 hours)	0.7	0.6	0.1	1.2	0.5	1.1
Color ΔE – 3 (1000 hours)	1.4	1.6	0.2	8.6	4.9	1.3
Color ΔE – 3 (1500 hours)	1.8	1.7	0.2	8.8	8.2	1.0
Color ΔE – 3 (2000 hours)	2.4	1.6	0.2	9.3	10.2	1.3
Color ΔE – 3 (2500 hours)	2.9	1.2	0.2	10.1	11.4	1.7
Color ΔE – 3 (2000 hours)	3.8	1.2	0.2	10.9	12.4	2.1

Figure 32 below shows sample panels at 2000 hours of weathering. In order, the panels are:

- **Top Far Left –** A control gloss white panels, not included in the data as there is no gloss white UV-curable coating to compare against.
- **Top Center Left –** Control Gray 36173
- **Top Center Right –** Control Black 37038
- **Top Far Right –** Control Gray 36173 APC
- **Bottom Left –** UV Gray 36173
- **Bottom Center –** UV Gray 36118
- **Bottom Right –** UV Black 37038

Figure 32. Weathered Panels at 2000 Hours

Analysis

Success/Failure Criteria: The success for minimum performance criteria of 500 hours is a ΔE color change of ≤1 and a 60° gloss of ≤5. There is no post-weathering 85° gloss requirement; 85° gloss readings are included for informational purposes only. A Failure by three units or less will be considered a “marginal failure” for purpose of adding nuance to the results analysis.

Coating Color: In all cases, the control coatings met specification requirements for color. The UV Gray 36173 had a color change delta of less than 1 for two out of 3 samples at 500 hours, and the third sample was a marginal failure. The UV Gray 36118 had a color change delta of less than 1 all three samples at 500 hours, meeting the minimum performance requirement. The UV Black 37038 showed a marginal failure color change for all three samples.

At 1000 hours and up, the situation changed. The Control Gray 36173 and the Control Black 37038 became marginal failures, exceeding a color change of 1 and gradually creeping upwards with increased exposure. The Control Gray 36173 APC, the only coating designed to meet optimum performance requirements, maintained a color change of less than 1 throughout the test. The UV Gray 36173 and UV Gray 36118 had a tremendous color change at 1000 hours and up, climbing to 8 units or more for most samples. The UV Black 37038, however, maintained its color better than either of the UV grays, not deviating much from the marginal failure values measured at 500 hours. Overall it seems that the UV-curable coatings are at the minimum edge of acceptability for 500 hour color change, and the UV Black 37038 is relatively close to meeting the optimum performance requirement for color change.

Coating Gloss: In all cases, the control coatings met specification requirements for gloss after 500 hours. All UV-curable coatings met the specification requirements for gloss after 500 hours, even in cases where (as with the UV Gray 36173 and UV Black 37038) they did not meet specification requirements for gloss at 0 hours. This trend continued for the 60 degree gloss after 500 hours, with the UV coatings gradually losing 60 degree gloss. There is no specification 85° gloss requirement

Film Thickness: Because color and gloss are determined by surface cure, it is not anticipated that a high dry film thickness will have a large effect on those properties. There does not seem to be a strong connection between coating thickness and color change or gloss.

3.9. Accelerated Weathering (flexibility)

Test Description

This test is described under Section 5.2.3.4.3 of this Final Report. This test determines the ability of a coated sample to withstand accelerated weathering in a weatherometer chamber when tested in accordance with ASTM G 155, Standard Practice for Operating Xenon Arc Light Apparatus for Exposure of Non-Metallic Materials. At the conclusion of 500 hours, Low Temperature Flexibility and GE Impact Flexibility of the coatings were tested for three flexibility panels of each type. At the conclusion of 3,000 hours, the Low Temperature Flexibility and GE Impact Flexibility of the coatings were tested for three flexibility panels of each type, representing the optimum performance requirements. The optimum performance criteria is no cracking or adhesion loss for a 2 inch cold mandrel bend and GE Impact Flexibility of 20% after 3,000 hours.

Results

Three panels for each coating were specifically designated for low temperature mandrel bend testing and three panels were designated for GE Impact testing at 500 hours, and another six panels were designated for testing at 3,000 hours. The data for each panel at 500 hours is shown as Table 76, and for each panel at 3,000 hours is shown as Table 77. Note that as flexibility panels do not include a primer layer in the coating stack-up, the specification coating stack-up thickness is 1.7 to 2.3 mils.

Table 76. Accelerated Weathering 500 Hour Flexibility Testing Data

1 Trial/panel	Control Gray 36173	Control Black 37038	Control Gray 36173 (APC)	Deft UV Gray 36173	Deft UV Gray 36118	Deft UV Black 37038
Mandrel – 1 (500 hours)	Pass	Pass	Pass	Pass	Pass	Pass
Thickness	2.5	1.9	2.9	2.4	3.7	2.3
Mandrel – 2 (500 hours)	Pass	Pass	Pass	Pass	Pass	Pass
Thickness	2.3	1.9	3.0	1.8	3.6	2.5
Mandrel – 3 (500 hours)	Pass	Pass	Pass	Pass	Pass	Pass
Thickness	2.6	2.0	2.7	2.3	3.7	2.7
GE Impact - 1 (500 hours)	10%	10%	10%	2%	1%	5%
Thickness	2.6	2.0	2.7	2.0	3.8	1.9
GE Impact - 1 (500 hours)	10%	10%	10%	2%	1%	5%
Thickness	2.4	2.1	3.0	2.3	3.6	1.8
GE Impact - 1 (500 hours)	10%	10%	10%	1%	1%	5%
Thickness	2.6	2.0	3.0	2.3	4.1	1.8

Table 77. Accelerated Weathering 3000 Hour Flexibility Testing Data

1 Trial/panel	Control Gray 36173	Control Black 37038	Control Gray 36173 (APC)	Deft UV Gray 36173	Deft UV Gray 36118	Deft UV Black 37038
Mandrel – 1 (3000 hours)	Pass	Pass	Pass	Pass	Fail	Pass
Thickness	2.4	2.1	2.7	1.8	3.7	1.8
Mandrel – 2 (3000 hours)	Pass	Pass	Pass	Pass	Fail	Pass
Thickness	2.5	2.3	2.6	2.0	3.4	2.0
Mandrel – 3 (3000 hours)	Pass	Pass	Pass	Pass	Fail	Pass
Thickness	2.7	2.2	2.9	1.9	3.5	2.2
GE Impact - 1 (3000 hours)	10%	20%	10%	1%	0%	10%
Thickness	2.7	1.9	2.6	2.0	3.9	1.8
GE Impact - 1 (3000 hours)	10%	20%	10%	2%	0%	10%
Thickness	2.4	2.1	2.7	2.3	3.9	1.7
GE Impact - 1 (3000 hours)	10%	20%	10%	0%	0%	10%
Thickness	2.6	2.1	2.6	3.1	3.6	1.8

Analysis

Success/Failure Criteria: As per the specification, the mandrel bend test will require a "Pass" and the GE Impact test will require a minimum 20%.

Low Temperature Mandrel Bend: All coating samples passed the cold mandrel bend test at 500 hours. At 3,000 hours, only the Deft UV Gray 36118 failed, suggesting that the coating had lost all flexibility after the extended weathering exposure.

GE Impact: At 500 hours, all coatings failed with a performance of 10% or worse. The control coatings were consistently at 10%, the UV Black 37038 was consistently at 5%, and the UV Gray coating samples all read at 2% and below. There is no obvious connection between coating thickness and performance in the GE impact flexibility test. At 3000 hours the results were similar, but two of the coatings showed a consistent increased flexibility over the 500 hours data. The Control Black 37038 achieved a passing flexibility of 20%, and the Deft UV Black 37038 improved to consistently 10%. It is unknown why black coatings should show increased flexibility at the 3,000 hour exposure mark over the 500 hour exposure mark, but the results seem consistent across all three test panels for each coating.

Film Thickness: At 500 hours, the Control Gray 36173 and Control Gray APC 36172 were applied at less than a mil over the recommended thickness. The Control Black 37038 was applied within the recommended maximum thickness. At 500 hours, the UV Gray 36173 and UV Black 37038 dry film thickness readings were all within specification, with the exception of one panel of the UV 36173 that was slightly over the recommended maximum thickness. The UV Gray 36118 samples were all more than a mil over specification. Though the UV Gray 36118 samples were slightly less flexible than the UV Gray 36173, the difference between 1% and 2% is within the sensitivity limits of the test and not necessarily due to the increased coating thickness.

At 3,000 hours, the Control Gray 36173 and Control Gray APC 36172 were applied at less than a mil over the recommended thickness. The Control Black 37038 was applied within the recommended maximum thickness. At 500 hours, the UV Gray 36173 and UV Black 37038 dry film thickness readings were all within specification, with the exception of one panel of the UV 36173 that was slightly over the recommended maximum thickness. The UV Gray 36118 samples were all more than a mil over specification

3.10. Heat Resistance

Test Description

This test is described under Section 5.2.3.4.4 of this Final Report. This test method determines the ability of coatings to resist exposure to high temperatures without color change, loss of adhesion or loss of flexibility. Minimum target criteria required the coated panels be exposed to 250 ± 5 °F for no less than 60 minutes and show a color change ΔE of less than 1. Optimum Target Criteria required the coated panels be exposed to 350 ± 5 °F for no less than 4 hours and show a color change ΔE of less than 1, a cross hatch adhesion rating of 4A or higher, and pass a 2 inch mandrel bend.

Results

Three panels for each coating were created for each of the following tests: minimum requirements color change, optimum requirements low temperature flexibility testing, and optimum requirements color change and crosshatch adhesion. The data for each panel is shown as Table 78. Note that as flexibility panels do not include a primer layer in the coating stack-up, the specification coating stack-up thickness is 1.7 to 2.3 mils for the low temperature flexibility panels.

Table 78. Heat Resistance Testing Data

	Control Gray 36173	Control Black 37038	Control Gray 36173 (APC)	Deft UV Gray 36173	Deft UV Gray 36118	Deft UV Black 37038
Min Req. Color ΔE - 1	0.1	0.1	0.1	0.9	0.3	0.2
Thickness	3.1	3.1	3.2	3.1	4.3	4.6
Min Req. Color ΔE - 2	0.1	0.1	0.1	0.9	0.3	0.1
Thickness	3.2	2.9	3.8	3.0	4.4	4.1
Min Req. Color ΔE - 3	0.1	0.1	0.1	0.8	0.3	0.3
Thickness	3.0	3.1	3.5	3.0	3.9	5.0
Opt Req. Color ΔE - 4	0.8	0.2	0.7	7.4	2.7	0.7
Thickness	3.2	3.0	3.6	3.2	4.0	3.0
Opt Req. Color ΔE - 5	1.1	0.1	0.7	7.5	2.8	0.7
Thickness	3.2	2.9	3.5	3.2	4.2	3.0
Opt Req. Color ΔE - 6	0.8	0.1	0.7	7.4	2.8	0.6
Thickness	3.3	2.9	3.2	3.3	3.9	2.6
Crosshatch - 4	4B	4B	5B	5B	5B	5B
Thickness	***	***	***	***	***	***
Crosshatch - 5	4B	4B	5B	5B	5B	5B
Thickness	***	***	***	***	***	***
Crosshatch - 6	4B	4B	5B	5B	5B	5B
Thickness	3.3	***	***	***	***	***
Low Temp Flex - 7	Pass	Pass	Pass	Pass	Pass	Pass
Thickness	2.4	1.8	2.8	2.3	3.7	1.8
Low Temp Flex - 8	Pass	Pass	Pass	Pass	Pass	Pass
Thickness	2.4	2.0	2.9	2.5	3.5	1.6
Low Temp Flex - 9	Pass	Pass	Pass	Pass	Pass	Pass
Thickness	2.3	2.1	2.8	2.0	3.6	1.7

*** - Same panels as optimum requirements color change.

Analysis

Success/Failure Criteria: The minimum target criteria is to show a color change ΔE of ≤1. The optimum performance criteria is to show a color change ΔE of ≤1, a cross hatch adhesion rating of 4A or higher, and pass a 2 inch low temperature flexibility mandrel bend.

Color: All coatings passed the minimum requirements color change test. One of the Control Gray 36173 panels returned very marginal failure on the optimum requirements test, with a ΔE of 1.1. Otherwise all the control panels passed the optimum requirements test. Both UV Gray coatings failed the optimum requirements color change test, but the UV Black 37038 passed the optimum requirements color change requirement.

Crosshatch Adhesion: All the coatings passed the optimum requirements cross hatch adhesion.

Low Temperature Flexibility: All the coatings passed the optimum requirements low temperature flexibility.

3.11. Humidity Resistance

Test Description

This test is described under Section 5.2.3.4.5 of this Final Report. This test method determines the ability of a coated sample to withstand exposure to high humidity when. The samples were exposed for 30 days in a humidity cabinet maintained at 120 ± 3 °F (49 ± 2 °C) and 100% RH. After exposure, the samples were visually evaluated for blistering, pencil hardness tested for softening, and given a cross hatch adhesion test.

Results

The same three panels for each coating were used for visual observation, pencil hardness, and crosshatch adhesion. The data for each panel is shown as Table 79.

Table 79. Humidity Resistance Testing Data

	Control Gray 36173	Control Black 37038	Control Gray 36173 (APC)	Deft UV Gray 36173	Deft UV Gray 36118	Deft UV Black 37038
Visual - 1	Pass	Pass	Pass	Fluid-filled blisters along the surface of the panel. Adversely affected physical test results -- no space on panel w/out blisters.	Small fluid-filled blisters on panel surface. Far enough apart to find test areas that were blister-free.	Very few blisters on panel (2 to 3 per panel). Water marks present on panel coated surface.
Thickness	2.8	2.8	3.2			
Visual - 2	Pass	Pass	Pass			
Thickness	2.9	3.1	3.5			
Visual - 3	Pass	Pass	Pass			
Thickness	2.9	3.0	2.8			
Hardness - 1	4H	4H	5H	F	H	H
Thickness	***	***	***	2.4	4.4	3.0
Hardness - 2	4H	4H	5H	F	H	H
Thickness	***	***	***	2.5	4.5	3.1
Hardness - 3	4H	4H	5H	F	H	H
Thickness	***	***	***	2.3	4.5	3.1
Presoak Avg. Hardness	3H	3H to 4H	4H	2H to 3H	H to 2H	2H to 3H
Crosshatch - 1	4B	4B	4B	1B	0B	5B
Thickness	***	***	***	***	***	***
Crosshatch - 2	4B	4B	4B	0B	0B	4B
Thickness	***	***	***	***	***	***
Crosshatch - 3	4B	4B	4B	0B	0B	4B
Thickness	***	***	***	***	***	***

*** - For each coating, the same three panels were used for all visual, hardness, and adhesion readings.

Analysis

Success/Failure Criteria: The success criteria are for no blistering, softening, loss of adhesion to occur. Blistering was observed visually, while cross hatch adhesion and pencil hardness were used to determine loss of adhesion and hardness.

Visual Observation: The three control coatings showed no visible blistering, while the three UV-curable coatings all showed blisters. Of these, the UV Black 37038 performed best, showing only a few blisters.

Pencil Hardness: All coatings showed some pencil hardness reduction, though no coating softened past an "F" value.

Crosshatch Adhesion: The control coatings all passed cross hatch adhesion. The UV Gray coatings showed minimal cross hatch adhesion, but the laboratory technician noted this was partially an effect of having so few areas without blisters that it was difficult to run a cross hatch test. The UV Black 37038 passed cross hatch adhesion.

3.12. Cleanability

Test Description

This test method is described in Section 5.2.3.4.6 of this Final Report. It determines the ability of coatings to maintain a cleaning efficiency of not less than 75%. Black panels were not tested, as their color makes it impossible to determine how well they have been cleaned. The gray panels were deliberately soiled and then cleaned, with the color change before and after the soil/cleaning cycle used to determine their cleanability rating.

Results

The same three panels for each coating were used for cleaning efficiency. The data for each panel is shown as Table 80.

Table 80. Cleanability Testing Data

	Control Gray 36173	Control Gray 36173 (APC)	Deft UV Gray 36173	Deft UV Gray 36118
Cleaning Efficiency - 1	93.69%	86.04%	35.86%	94.67%
Thickness	3.3	3.4	2.6	4.2
Cleaning Efficiency - 2	93.69%	87.24%	28.46%	96.60%
Thickness	3.0	3.3	2.3	4.1
Cleaning Efficiency - 3	93.28%	89.95%	31.80%	96.46%
Thickness	3.3	3.1	2.4	3.8

Analysis

Success/Failure Criteria: To be successful, the panels must show a cleanability of 75% or greater.

Cleaning Efficiency: Both controls passed the cleanability requirement. The Deft UV Gray 36118 passes as well, but the Deft UV Gray 36173 failed by a large margin. It is unknown why results on the two UV-curable coatings were so dissimilar.

3.13. Salt Spray Test

Test Description

This test is described in Section 5.2.3.4.7 of this Final Report. It covers the corrosion resistance properties of test specimens placed in a controlled corrosive heated environment for a specified length of time in accordance with ASTM B-117, *Standard Practice for Operating Salt Fog Apparatus*. These panels are scribed and placed in a salt solution is verified to be 5% +/- 1% and pH is verified to be 6.5 to 7.2 at 35° C. The chamber is closed and the specimens are evaluated for surface corrosion and creepage from scribe every 500 hours for 2000 hours total.

Results

The same three panels for each coating were used for visual observation of the salt spray impacts. The data for each panel is shown as Table 81. Note that no panels were created for the Control Black 37038 due to an error in laboratory production. Note also that observations at the 500 hour mark were not recorded consistently. Only the final 2000 hour observations were provided for all coatings.

Table 81. Salt Spray Testing Data

Visual Observations	Control Gray 36173	Control Black 37038	Control Gray 36173 (APC)	Deft UV Gray 36173	Deft UV Gray 36118	Deft UV Black 37038
1000 Hours - 1	No Data	No Data	No Data	No Data	No Data	No Data
Thickness	2.5	No Data	3.1	2.9	3.7	2.8
1000 Hours - 2	No Data	No Data	No Data	No Data	No Data	No Data
Thickness	2.5	No Data	3.2	2.6	3.8	2.9
1000 Hours - 3	No Data	No Data	No Data	No Data	No Data	No Data
Thickness	2.6	No Data	3.0	2.8	3.5	2.8
1500 Hours - 1	No Data	No Data	No Data	Blistering	Blistering; topcoat comes off at touch	Blistering; topcoat comes off at touch
Thickness	***	No Data	***			
1500 Hours - 2	No Data	No Data	No Data			
Thickness	***	No Data	***			
1500 Hours - 3	No Data	No Data	No Data			
Thickness	***	No Data	***			
2000 Hours - 1	Mild pitting in scribe	No Data	Serious discoloration from scribe	Topcoat removal	Mild pitting in scribe	Serious discoloration from scribe
Thickness		No Data				
2000 Hours - 2		No Data		Blistering		
Thickness		No Data				
2000 Hours - 3		No Data		Topcoat removal		
Thickness		No Data				

<u>Analysis</u>

Success/Failure Criteria: The criteria is no blisters or undercutting from the scribe; no discoloration in the scribe and no pitting in the scribe.

Analysis: The three UV-curable coatings performed extremely poorly compared to the controls, continuing the pattern of poor performance in a humid environment for these coatings.

Visual Observation: Panels are shown in Figure 33 below at 2,000 hours.

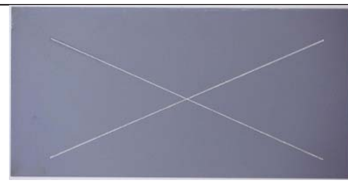
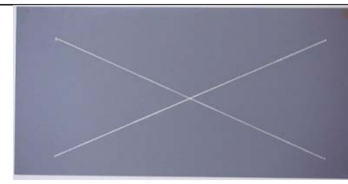
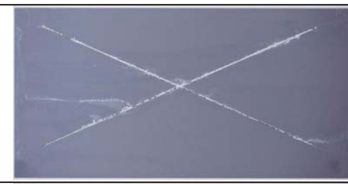
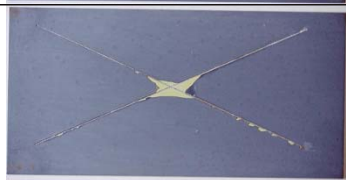
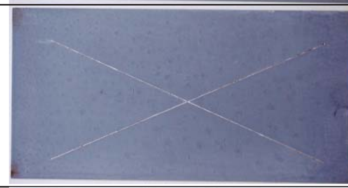
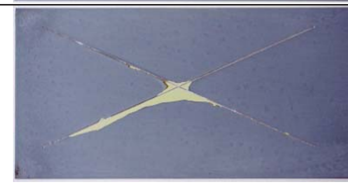
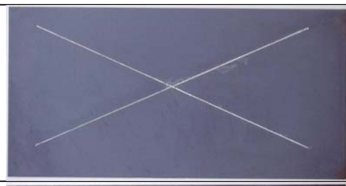
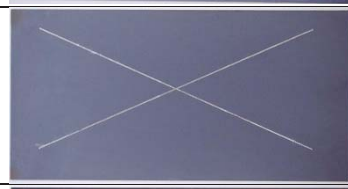
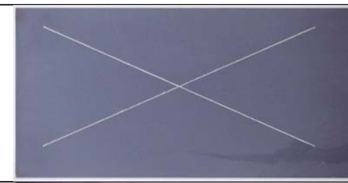
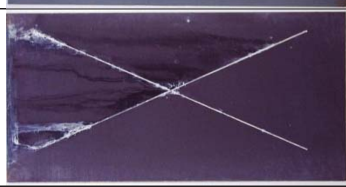
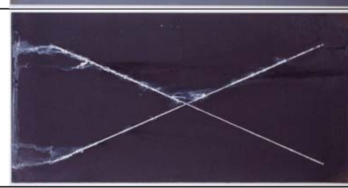
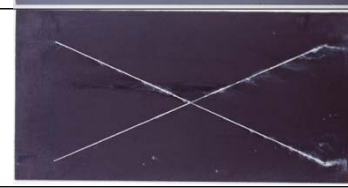
Coating	Panel 1	Panel 2	Panel 3
Control Gray 36173			
Control Gray 36173 (APC)			
Deft UV Gray 36173			
Deft UV Gray 36118			
Deft UV Black 37038			

Figure 33. Salt Spray Panels at 2000 Hours

3.14. Repairability

<u>Test Description</u>

This test is described in Section 5.2.3.5 of this Final Report. The test determines the ability of UV-curable coatings to adhere to itself, to standard MIL-PRF-85285 topcoat, or to an APC-qualified MIL-PRF-85285 topcoat during standard repair scenarios. Repair Scenarios are:

6) UV-curable used to repair weathered MIL-PRF-85285 topcoat

7) UV-curable used to repair weathered APC-qualified MIL-PRF-85285 system

8) UV-curable used to repair weathered UV-cure coating system

9) MIL-PRF-85285 topcoat used to repair weathered UV-cure coating system

10) APC MIL-PRF-85285 topcoat used to repair weathered UV-cure coating system

For each repair, half the panel will have a primer applied before the repair topcoat is laid down, and the other half of the panel will have the repair topcoat applied without a light spray of primer. This was done to simulate the two most common field repair scenarios. A wet tape and cross hatch adhesion test is performed on each side.

Results

The same three panels for each coating were used for 500 hour gloss at 60 degrees, 500 hour gloss at 85 degrees, and 500 hour color. Two of those panels for each coating were used for primed wet tape adhesion, primed crosshatch adhesion, unprimed wet tape adhesion, and unprimed crosshatch adhesion. The data for each panel is shown as Table 82 and 83.

Table 82. Repairability of UV on Controls

	Deft UV Gray 36173	Deft UV Gray 36118	Deft UV Black 37038
Unprimed Wet Tape – 85285 Base	0A	2A	4A
Unprimed Wet Tape – APC Base	0A	5A	4A
Unprimed Wet Tape – UV Base	0A	4A	4A
Unprimed Crosshatch - 85285 Base	0B	0B	3B
Unprimed Crosshatch – APC Base	0B	0B	3B
Unprimed Crosshatch – UV Base	0B	1B	3B
Primed Wet Tape - 85285 Base	3A	5A	5A
Primed Wet Tape - APC Base	3A	5A	5A
Primed Wet Tape - UV Base	4A	4A	4A
Primed Crosshatch - 85285 Base	0B	4B	4B
Primed Crosshatch - APC Base	0B	3B	4B
Primed Wet Tape - UV Base	0B	0B	3B

Table 83. Repairability of Controls on UV

	Control Gray 36173	Control Gray 36173 (APC)
Unprimed Wet Tape – UV 36173 Base	4A	4A
Unprimed Wet Tape – UV 36118 Base	4A	4A
Unprimed Wet Tape – UV 37038 Base	4A	4A
Unprimed Crosshatch – UV 36173 Base	4B	4B
Unprimed Crosshatch – UV 36118 Base	4B	3B
Unprimed Crosshatch – UV 37038 Base	4B	4B
Primed Wet Tape – UV 36173 Base	5A	5A
Primed Wet Tape – UV 36118 Base	4A	4A
Primed Wet Tape – UV 37038 Base	4A	4A
Primed Crosshatch – UV 36173 Base	4B	4B
Primed Crosshatch – UV 36118 Base	4B	4B
Primed Crosshatch – UV 37038 Base	4B	4B

Analysis

Success/Failure Criteria: The success criteria are to avoid any peel away and show a rating of 4A or 5A for wet tape adhesion and 4B or 5B for cross hatch adhesion. Lack of adhesion on unprimed surfaces may be indicative of the need for proper primer activation of the surface rather than a failure of the coating.

Wet Tape Adhesion - Primed: The control coatings adhered to all UV coatings. The UV Gray 36118 and UV Black 37038 showed wet tape adhesion to primed panels. The UV Gray 36173 marginally failed wet tape adhesion tests to control coatings but passed adhesion to itself.

Crosshatch Adhesion - Primed: The control coatings adhered to all UV coatings. The UV Gray 36118 and UV Black 37038 showed adhesion to the primed panels, with a marginal failure of the UV Gray 36118 for crosshatch adhesion to an APC panel and a complete failure of UV Gray 36118 to adhere to itself. The UV Gray 36173 showed extremely poor adhesion to 85285, APC base panels, and itself, receiving a zero rating in all crosshatch adhesion tests.

Wet Tape Adhesion - Unprimed: The control coatings adhered to all UV coatings. The UV Black 37038 showed wet tape adhesion to all coatings. The UV Gray 36118 adhered to APC and itself, but received a 2A rating for adhesion to 85285. The UV Gray 36173 showed extremely poor adhesion to 85285, APC base panels, and itself, receiving a zero rating in all crosshatch adhesion tests.

Crosshatch Adhesion - Unprimed: The control coatings adhered to all UV coatings. The UV coatings failed all unprimed cross hatch adhesion tests, though the UV Black 37038 failed only marginally.

3.15. Stripability

These tests are described in Section 5.2.3.6 of this Final Report. They test the ability of various coating removal methods to remove UV coatings as compared to ability to remove control coatings. The performance criteria is established as visual confirmation of complete coating removal when stripped method is applied as per current established procedures.

Test Description

A. Chemical Removers

This test covers a procedure for establishing ability of chemical paint removers to remove the UV coatings as compared with removal of the control paint systems.

B. Blast Media Removers

This test covers a procedure for establishing ability of blast media to remove the UV coatings as compared with removal of the control paint systems.

C. Laser Coating Removal System

This test covers a procedure for establishing ability of a 6000W fiber laser system to remove the UV coatings as compared with removal of the control paint systems.

Results

Three panels for each coating were specifically designated for chemical remover testing, three panels were specifically designated for blast media remover, and three panels were designated for laser coating removal system. The data for each panel is shown as Table 84.

Table 84. Stripability Testing Data

	Control Gray 36173	Control Black 37038	Control Gray 36173 (APC)	Deft UV Gray 36173	Deft UV Gray 36118	Deft UV Black 37038
Chemical - 1	4-hr blistering, 19-hr complete removal	4-hr 25% blistered, 19-hr 90% blistered	4-hr 0% blistered, 19-hr 40% blistered	20-min blistering, 4-hr 90%, 19-hr 100%, TC	60-min blistering, 4-hr 85%, 19-hr 100%, TC	4-hr 0% blistered, 19-hr 33%, TC & P
Thickness	2.6	2.8	3.2	2.7	4.0	3.9
Chemical - 2	4-hr blistering, 19-hr complete removal	4-hr 25% blistered, 19-hr 90% blistered	4-hr 0% blistered, 19-hr 40% blistered	60-min blistering, 4-hr 90%, 19-hr 100%, TC	60-min blistering, 4-hr 85%, 19-hr 100%, TC	4-hr 0% blistered, 19-hr 33%, TC & P
Thickness	2.7	3.1	3.2	3.1	4.0	4.0
Chemical - 3	4-hr blistering, 19-hr complete removal	4-hr 25% blistered, 19-hr 90% blistered	4-hr 0% blistered, 19-hr 40% blistered	60-min blistering, 4-hr 90%, 19-hr 100%, TC	60-min blistering, 4-hr 85%, 19-hr 100%, TC	4-hr 0% blistered, 19-hr 33%, TC & P
Thickness	2.8	3.2	3.4	2.8	3.7	4.1
Blast - 1	Complete removal in 13 sec.	Complete removal in 10 sec.	Complete removal in 9 sec.	Complete removal in 5 sec.	Complete removal in 6 sec.	Complete removal in 7 sec.
Thickness	3.1	3.0	3.1	2.6	3.9	4.1
Blast - 2	Complete removal in 12 sec.	Complete removal in 11 sec.	Complete removal in 9 sec.	Complete removal in 5 sec.	Complete removal in 6 sec.	Complete removal in 9 sec.
Thickness	3.4	3.0	3.0	3.1	3.1	4.2
Blast - 3	Complete removal in 12 sec.	Complete removal in 9 sec.	Complete removal in 10 sec.	Complete removal in 6 sec.	Complete removal in 5 sec.	Complete removal in 10 sec.
Thickness	3.4	2.7	2.7	3.3	3.3	4.3
Laser - 1	Removal Rate = 0.18 ft^2/min	Removal Rate = 0.18 ft^2/min	Removal Rate = 0.29 ft^2/min	Removal Rate = 0.25 ft^2/min	Removal Rate = 0.18 ft^2/min	Removal Rate = 0.25 ft^2/min
Thickness	2.9	2.8	2.9	2.5	2.5	3.5
Laser - 2	Removal Rate = 0.19 ft^2/min	Removal Rate = 0.32 ft^2/min	Removal Rate = 0.23 ft^2/min	Removal Rate = 0.29 ft^2/min	Removal Rate = 0.20 ft^2/min	Removal Rate = 0.20 ft^2/min
Thickness	3.0	2.6	2.8	2.9	2.9	3.2
Laser - 3	Removal Rate = 0.21 ft^2/min	Removal Rate = 0.31 ft^2/min	Removal Rate = 0.21 ft^2/min	Removal Rate = 0.31 ft^2/min	Removal Rate = 0.19 ft^2/min	Removal Rate = 0.26 ft^2/min
Thickness	3.0	2.5	2.5	3.1	3.1	3.1

Analysis

Success/Failure Criteria: A visual inspection should show complete coating removal at speeds comparable to that of the controls.

All Removal Methods: For all coating removal methods, the UV-curable coatings were able to be removed at speeds comparable to that of control coatings, with no difficulties experienced.

3.16. Environmental Conditions Testing

Test Description

This test is described in Section 5.2.3.2.5 of this Final Report. The test's purpose is to validate cure capability in less than favorable conditions. For each UV-curable topcoat, one set of three (3) panels utilizing that UV topcoat shall be cured at the following environmental conditions:

- 77° ± 5° Fahrenheit (ºF) / 50 ± 5% Relative Humidity (RH) (**control temperature**)
- 90° ± 5 ºF / 80% ± 5% RH (**hot/wet**)
- 90° ± 5 ºF / 20% ± 5% RH (**hot/dry**)
- 60°± 5 ºF / 80% ± 5% RH (**cold/wet**)
- 60° ± 5 ºF / 20% ± 5% RH (**cold/dry**)

Each panel shall be subjected to wet tape and cross hatch adhesion.

Results

The data for each panel is shown in Table 85 and Table 86.

Table 85. Environmental Conditions Test – Wet Tape

	Deft UV Gray 36173	Deft UV Gray 36118	Deft UV Black 37038
Wet Tape – 77° ± 5° ºF / 50 ± 5% RH - 1	0A	4A	4A
Wet Tape – 77° ± 5° ºF / 50 ± 5% RH - 2	0A	4A	4A
Wet Tape – 77° ± 5° ºF / 50 ± 5% RH - 3	0A	4A	4A
Wet Tape – 90° ± 5 ºF / 80% ± 5% RH - 1	2A	4A	2A
Wet Tape – 90° ± 5 ºF / 80% ± 5% RH - 2	1A	4A	4A
Wet Tape – 90° ± 5 ºF / 80% ± 5% RH - 3	2A	4A	4A
Wet Tape – 90° ± 5 ºF / 20% ± 5% RH - 1	0A	0A	0A
Wet Tape – 90° ± 5 ºF / 20% ± 5% RH - 2	0A	0A	0A
Wet Tape – 90° ± 5 ºF / 20% ± 5% RH - 3	0A	0A	0A
Wet Tape – 60°± 5 ºF / 80% ± 5% RH - 1	5A	1A	0A
Wet Tape – 60°± 5 ºF / 80% ± 5% RH - 2	0A	1A	0A
Wet Tape – 60°± 5 ºF / 80% ± 5% RH - 3	1A	3A	0A
Wet Tape – 60° ± 5 ºF / 20% ± 5% RH - 1	1A	0A	0A
Wet Tape – 60° ± 5 ºF / 20% ± 5% RH - 2	1A	0A	0A
Wet Tape – 60° ± 5 ºF / 20% ± 5% RH - 3	1A	0A	0A

Table 86. Environmental Conditions Test – Crosshatch

	Deft UV Gray 36173	Deft UV Gray 36118	Deft UV Black 37038
Crosshatch – 77° ± 5° ºF / 50 ± 5% RH - 1	2B	5B	5B
Crosshatch – 77° ± 5° ºF / 50 ± 5% RH - 2	3B	5B	5B
Crosshatch – 77° ± 5° ºF / 50 ± 5% RH - 3	3B	5B	5B
Crosshatch – 90° ± 5 ºF / 80% ± 5% RH - 1	4B	5B	5B
Crosshatch – 90° ± 5 ºF / 80% ± 5% RH - 2	4B	5B	5B
Crosshatch – 90° ± 5 ºF / 80% ± 5% RH - 3	4B	4B	5B
Crosshatch – 90° ± 5 ºF / 20% ± 5% RH - 1	0B	1B	4B
Crosshatch – 90° ± 5 ºF / 20% ± 5% RH - 2	0B	2B	4B
Crosshatch – 90° ± 5 ºF / 20% ± 5% RH - 3	0B	1B	4B
Crosshatch – 60°± 5 ºF / 80% ± 5% RH - 1	5B	4B	5B
Crosshatch – 60°± 5 ºF / 80% ± 5% RH - 2	4B	4B	5B
Crosshatch – 60°± 5 ºF / 80% ± 5% RH - 3	4B	4B	4B
Crosshatch – 60° ± 5 ºF / 20% ± 5% RH - 1	0B	1B	0B
Crosshatch – 60° ± 5 ºF / 20% ± 5% RH - 2	1B	2B	2B
Crosshatch – 60° ± 5 ºF / 20% ± 5% RH - 3	0B	2B	0B

Analysis

Success/Failure Criteria: The standard acceptance criteria were no peel away with a target rating of 4A or 5A for wet tape adhesion, or 4B or 5B for cross hatch adhesion. 3A or 3B will be considered a marginal failure.

Wet Tape Adhesion: The Deft UV Gray 36173 coating did not pass wet tape adhesion under any environmental conditions, even those of laboratory control. This is consistent with the behavior of the coating under the base wet tape adhesion testing as shown in Table 5 under section 3.2. The Deft UV Gray 36118 passed wet tape adhesion under control environmental conditions and hot/wet environmental conditions, but not under hot/dry, cold/dry, or cold/wet conditions. The Deft UV Black 37038 performed similarly.

Crosshatch Adhesion: The Deft UV Gray 36173 coating passed cross hatch adhesion under dry/wet and cold/wet conditions, but not other conditions. The Deft UV Gray 36118 passed cross hatch adhesion under control environmental conditions, hot/wet, and cold/wet environmental conditions, but not under hot/dry or cold/dry. The Deft UV Black 37038 passed cross hatch under every condition except cold/dry.

Overall: Cold/dry is the only condition in which both wet tape and cross hatch adhesion were failed by all three coatings. However, the constant variation of adhesion results among tests in this JTP make it difficult to conclusively determine a consistent effect of temperature and humidity on coating cure.

4. Overall Analysis

In many cases the results of testing the UV-curable coatings were inconsistent both with the vendor-reported laboratory test data reported in Section 6.2.1 and between the different UV-curable colors. Of the three UV-curable color formulations, the black performed the most consistently strongly. One explanation under consideration is that the MEK rub test is not sufficient indication of state of cure and some samples were not completely cured, skewing results.

APPENDIX F - TRIP REPORT FOR JULY 2010 VISIT TO OO-ALC

UV-Curable Coatings
Demonstration/Validation Trip to Hill AFB 7/13/2010 to 7/15/2010

Author: Matthew Campbell (Concurrent Technologies Corporation)

Executive Summary
The trip was intended to demonstrate UV-curable coatings as both stencil coatings (on an F-16 and C-130) and as topcoats (on a C-130). Review of laboratory testing data with the Principle Investigator (PI) concluded that results were not consistent enough to demonstrate coatings as a topcoat without further positive test data. Subsequently, a test run of the coatings on surfaces simulating the intended aircraft demonstration targets indicated a failure to achieve proper cure that did not match previous testing. The demonstration was not carried forward, and further demonstrations will be halted until the cause of coating failure has been identified and corrected.

Introduction
From July 13, 2010 to July 15, 2010, personnel traveled to Hill Air Force Base (AFB). The goal of this trip was to demonstrate ultraviolet (UV)-curable coatings developed under Environmental Security Technology Certification Program (ESTCP) Project WP-0804, UV-Curable Coatings for Aerospace Applications, for use as aerospace topcoats. This demonstration/validation (Dem/Val) effort was to be conducted as per the approved ESTCP Demonstration Plan.

Ultraviolet (UV)-curable coatings are a potential alternative to solvent-borne organic coatings. UV-curable coatings are virtually VOC, HAP, and isocyanate-free. They are single component, high-solids (nearly 100%), cross-linked coatings that are cured in minutes by brief exposure to intense UV light. Benefits of successful implementation of UV-curable coatings include:

- Reduced VOC and HAP emissions
- Reduced hazardous waste
- Reduced waste management costs
- Reduced regulatory financial liabilities
- Enhanced environmental leadership role
- Minimal capital investment [applied through current spray technology, high volume low pressure (HVLP) and traditional coating techniques (i.e., brush, roll or spray)]
- Decreased process flow time
- Increased weapon system availability

This ESTCP project is a joint service effort involving stakeholders from the United States Air Force (USAF), United States Navy (USN), and United States Coast Guard (USCG). Hill AFB is the primary stakeholder for this effort and the target for implementation.

Dem/Val Targets

The colors of the Deft UV-curable topcoat were brought onsite for the Dem/Val. These batches of formulation were mixed for the Dem/Val in mid-June 2010. The Deft identification numbers, FED-STD-595 color numbers, and Deft Batch numbers are listed in Table 87 below.

Table 87. Deft UV-Curable Topcoats

Deft Identification	Color	Batch Number
21GY001	36173 Gray	200-63
21GY002	36118 Gray	200-64
21BK003	37038 Black	200-65

For ease of readability and familiarity, these Deft formulations will henceforth be referred to by their FED-STD-595 color numbers from this point forward. For instance, 21GY002 will be referred to as, "UV Gray 36118".

The target aircraft for this Dem/Val were one (1) F-16 aircraft out of Buckley AFB (tail number 8700000254) and one (1) C-130 aircraft out of Cheyenne AFB (tail number 937314). The target areas on each aircraft are listed in Table 88.

Table 88. Demonstration Targets

Demonstration Targets	**Coating Demonstrated**	**Stencil / Topcoat**
F-16 tail numbering and letters on right side	UV Gray 36118	Stencil
F-16 star and bars beneath right wing	UV Gray 36118	Stencil
F-16 rescue arrow, right side	UV Gray 36118	Stencil
C-130 propeller tips, #3 engine	UV Black 37038	Stencil
C-130 exhaust tracks, right side	UV Black 37038	Stencil
C-130 star emblem, right side	UV Black 37038	Stencil
C-130 escape hatch	UV Gray 36173	Topcoat
C-130 aft landing gear door	UV Gray 36173	Topcoat
C-130 battery box door	UV Gray 36173	Topcoat

After arrival on site, the CTC team was informed that the Cheyenne C-130 had fallen off the maintenance schedule completely. The team hoped to be able to pull the hatch and doors off the C-130 and paint them separately, but further investigation revealed that the aircraft had been placed on indefinite hold for investigation of faults found during testing and no activity of any sort would be authorized. A plan was made to move forward with the F-16 stencil demonstration and make a return trip when the Cheyenne C-130 was available. However subsequent review and events (detailed in the following sections) placed Dem/Val activities on indefinite hold.

July 13, 2010

Review of Dem/Val Plan

The CTC team arrived at 0730 and met with the PI. The team discussed the availability of our desired demonstration aircraft and our planned demonstration targets, as detailed in the previous section. (INFORMATIONAL NOTE: The PI indicated that a standard labor rate of $130.36/hour should be used for cost/benefit analyses involving man-hour labor at Hill AFB.)

During this discussion, the PI took the CTC team around the base to locate and view the demonstration target aircraft, assemble the 2400W H&S UV lamp for the demonstration, locate the Deft UV paint, assign a Hill painter to apply the UV paint, and otherwise prepare for the demonstration. One difficulty noted was that the power outlets in the F-16 paint bay are meant for explosion-proof plugs, and the UV lamp was not equipped with explosion-proof plugs. The PI arranged for purchase of a cord and plugs to enable a connection to be made.

JTP Results Review

After completion of these preliminary efforts, the PI and CTC team conducted a test-by-test review of the results of the Joint Test Protocol (JTP) testing conducted on the Deft topcoats at Battelle Memorial Laboratories. The JTP is a test plan approved by all project stakeholders that is heavily based off aerospace topcoat military specifications and represents the required performance properties for UV-curable coatings to be usable as DoD aerospace topcoats in the USAF, USN, and USCG. Battelle had not yet completed testing and submitted a full test report, so the results were in the format of an informal test report drafted using raw data submitted by Battelle.

The reviewers agreed that the results were not acceptable. Not only did the Deft coatings fail many requirements, but the failures were inconsistent in degree, frequency, and severity. Performance varied not only between each of the UV colors, but even multiple tests of the same UV color could show extremely different results. The control coatings were consistent in results and passed the majority of requirements. The JTP data does not match the results of manufacturer testing conducted prior to release of the coating.

The bottom line conclusion was that for eventual implementation, the coatings would have to be retested and show consistent results able to match the minimum performance test results of the controls. However, due to the year-long length of the planned field Dem/Val period, there was consideration as to whether the current version of coatings should proceed to field evaluation while explanations were sought for the inconsistency and poor performance compared to manufacturer reported data.

The PI indicated that his comfort level was not high enough to attempt to test the coatings as topcoats, though the stencil coating testing could proceed. He further indicated willingness to proceed with the C-130 topcoat demonstration without a full JTP repeat if a good explanation could be provided for the inconsistency of results and some follow-up testing conducted to confirm this explanation. The CTC team both concurred with this decision.

As a precaution, the PI had an “A-frame” prepared for the following day so that the planned on-aircraft UV-curable application could be simulated in the exact environmental conditions and coating interactions that would occur when UV coatings were applied to an aircraft. This A-frame will be fully described in the July 14, 2010, section of this report.

Landing Gear Shop Tour
After data review was completed, the three representatives from BMS arrived on base. After exchanging preliminary greetings, the PI took all visitors on a tour of the landing gear paint shop with the assistance of on-site support from AIS. The purpose of this tour was to demonstrate a recently installed infrared (IR) oven automated line being used to rapidly cure aircraft landing gear. A UV cure line might operate in a similar fashion, so the purpose of the tour was to give a sense for how such a line would have to operate to flexibly fit into depot operations.

During this tour and afterwards, the group discussed UV’s current use in automotive operations and the possibility of adapting coatings and techniques used there to aerospace maintenance operations. All visitors then departed for the day.

July 14, 2010
Representatives from CTC , BMS, Deft, and H&S Autoshot arrived on-site at 0700. The PI greeted all visitors and signed them in at security (as per the previous day), then took them to a conference room to review plans for the day.

Morning Meeting
After an overview by the PI of safety requirements for aircraft paint areas, lamp use procedure was reviewed with the H&S representatives. They reassured the group that the UVA light frequency of the lamp is harmless in indirect exposure, beyond distances of a few feet for direct exposure, or for brief time periods in direct close range skin exposure. It was reiterated that individuals working directly with the lamp should always wear polycarbonate safety glasses to prevent direct close range exposure to the eyes. Power requirements for the UV lamp were also discussed, with H&S stating that each head of the lamp draws about 11 amps on 110V line. It was also recommended that the lamp be allowed a minimum 3-minute warm-up period before use. BMS confirmed that the planned cure parameters of 10 minutes at 10 inches were acceptable for curing the coatings. These parameters were based on CTC’s experience with previous batches of the Deft coating in our laboratory testing.

The PI then led a discussion regarding the inconsistent results from the JTP testing, which BMS and Deft had previously been provided to review. Neither BMS nor Deft were able to explain the results, which they reiterated did not match their laboratory testing. Several theories were offered, including some procedural flaw in application/curing the panels for the laboratory testing. Issues discussed included lamps used, coating thickness, some difference in procedures, and/or potential formulation inconsistencies.

One note was that BMS uses a 400W H&S unit in development compared to the 1200W unit utilized to cure the coatings for laboratory testing. The 400W and 1200W units output in identical light spectra, but the 400W has a smaller cure area and is more intense within that cure area. However, the difference in intensity is not tremendous, and state-of-cure testing conducted at CTC and Battelle shows the 1200W is capable of fully curing the coatings.

The issue was tabled for the time being, and CTC, BMS, and Deft resolved to put together a plan to find the responsible factor(s) for the inconsistent and failing results.

The PI then led a brief tour of the C-130 and F-16 paint areas to better familiarize the H&S representatives with the requirements for a UV lamp usable in a depot maintenance environment. The safety requirement for a Class I, Division I, explosion-proof lamp is understood. The focus of the tour was therefore more about issues with the lamp's planned stand and support structure, ensuring that it will have the necessary attachments and portability to be used in combination with current and planned maintenance stands. Lamp development will be conducted under a separate and related effort, which is currently in proposal to the government.
(INFORMATIONAL NOTE: Gloss readings were taken on the 36173 APC topcoat of a newly C-130 attached to the Tennessee Air Guard. Gloss was 4@ 60° and 8@ 85°. The PI indicated that gloss readings near the allowable limit were preferred over extremely flat coatings.)

Dem/Val Set-up
The group ended in the F-16 paint area in an empty bay with the A-frame that the PI had ordered prepared. The target Buckley F-16 was located in the bay next door, having been given a topcoat the previous night, which was sufficiently cured for stencil application.

This A-frame consisted of two aluminum surfaces (thickness 0.09 inches) supported near-vertically on an A-shaped framework. Each surface was approximately 12 feet long by 4 feet in height. Both surfaces were painted with a PPG Coatings MIL-P-23377H primer, Type C2, at approximately 1500 on the previous day. After the primer was allowed to sit for 6 hours, one surface was sprayed with a PPG Coatings MIL-PRF-85285, Type 4 Advanced Performance Coating (APC) at approximately 2100 the night before. These surfaces will be referred to as "A-Frame Primed Surface" and "A-Frame APC Surface" respectively. The A-Frame is shown in Figures 34 and 35 below.

Figure 34. A-Frame Primed Surface

Figure 35. Inspection of A-Frame APC Surface

Dry Film Thickness (DFT) readings of the A-Frame Primed Surface showed an average thickness of approximately 1 mil. DFT readings of the A-Frame APC Surface showed variability in thickness, with readings of 3 to 4.5 mils, depending on the spot chosen.

The A-Frame Primed Surface was intended to emulate the demonstration target of using UV-curable 36173 Gray as a topcoat for large areas of a C-130 aircraft. An area of approximately 4.5' by 4' was taped off as representative of the largest targeted C-130 area, the aft landing gear door. The test area is shown in Figure 36 below, being taped off.

Figure 36. Primed Surface Test Area

The A-Frame APC Surface was intended to emulate the stencil targets on the F-16 aircraft. Three stencils made of the same Gerber maskant used for on-aircraft stencils were placed on the APC surface at approximately 1100 hours. They featured one "Rescue Arrow" (24" long by 6" wide at widest point), one "Star & Bars" (20" long by 11" wide at widest point), and one "Painted-At Tag" (maskant square 12" long by 8" wide). Figure 38 shows a view of all the stencil maskants at once, and Figures 37 through 40 shows each in detail.

Figure 37. APC Stencils

Figure 38. Rescue Arrow Stencil

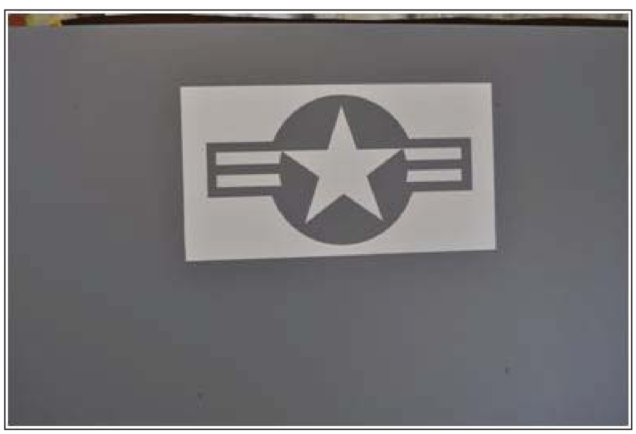


Figure 39. Star and Bars Stencil

Figure 40. Painted-At Tag Stencil

The most serious hold-up experienced at this time was supplying power to the demonstration lamp. The 2400W H&S lamp system used in the demonstration consists of two 1200W lamp heads, each with its own separate power supply, mounted on a single flexible stand system that allows manipulation of the heads to a variety of positions and directions. The lamp system is shown in Figure 41, extended and in use during a later phase of the demonstration.

Figure 41. UV Demonstration Lamp

The available power from the explosion-proof outlets at the back of the paint bay proved unable to support both UV lamp heads simultaneously, causing a circuit breaker to trip when the lamp was first powered on. Eventually an extension cord of over 200+ feet in length was procured and used to connect the lamp to available power in another portion of the building. Per H&S, the lamp is designed to compensate for power drops to a certain degree. Tests after the fact suggest that the lamp heads likely suffered a reduction in output mW of approximately 20%.

A-Frame Stencil Application

As the actual demonstration targets for the day were F-16 stencils, priority was given to verifying the ability of the UV 36118 to act as a successful stencil material. The UV 36118 paint was shaken in the paint shop and loaded into a HVLP application system. A paint shop worker from Hill AFB, was chosen to apply the coating to the maskant areas.

Before stencil application, DFT readings were taken within the region of each maskant where the stencil material would remain. The results were:

- Rescue Arrow – No areas large enough to take readings with available instrument.
- Star & Bars – Range of 3.1 to 4.3 mils, median around 3.5 mils.
- Painted-At Tag – 2.5 mils

Stencil application was begun at 1224, meaning the APC topcoat had been curing for approximately 15 hours. Ambient temperature of the APC surface was recorded as being 75° F using an infrared sensing unit. Each stencil took less than 30 seconds to apply, and the material seemed to flow well and present no difficulties in application. A wet film thickness (WFT) gauge was used to measure the thickness of the paint after each application to ensure a sufficient coat. Figure 42 shows the application process.

Figure 42. Stencil Application Process

WFT readings were as follows:

- Rescue Arrow – 3.5 mils
- Star & Bars – 3.5 mils
- Painted-At Tag – 3.5 mils

The 36118 material was then given a fifteen minute ‘flash-off’ time to allow all the exempt solvents in the material time to sublimate away. The lamp was turned on at 1227 to allow the bulbs plenty of time to fully heat and reach maximum intensity. During this time the lamp shutters were left closed so as to prevent any potential exposure to UV light scatter.

After the conclusion of the flash-off time, the lamp was positioned in front of the Painted-At Tag stencil at a stand-off of ten inches from the surface of the shutter to the surface of the stencil. The shutters remained closed during the positioning process to prevent premature cure. The shutters were then opened, and the stencil was exposed to UV light for ten minutes. Figure 43 shows the cure of the Painted-At Tag.

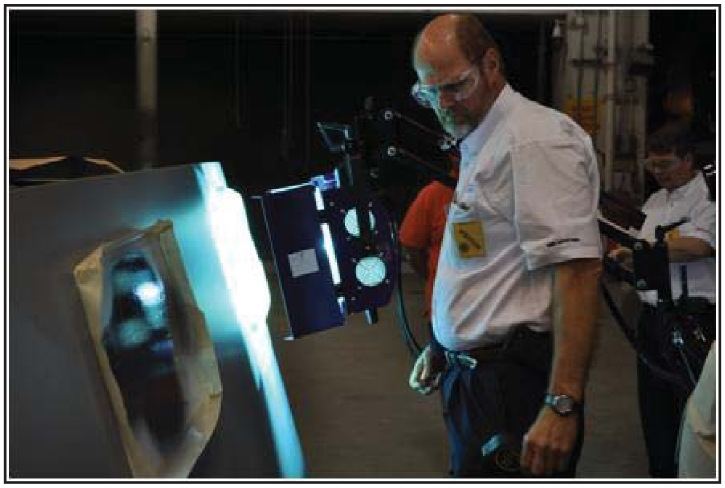


Figure 43. UV Cure of Painted-At Tag

During this cure, the IR temperature gauge was used to take the temperature of the substrate of the light at one minute increments. It is uncertain how accurate these readings are, as the UV light may have interfered with the IR sensor. However the final reading was taken just after the lamp shutters were closed and the light removed, presumably showing the highest temperature reached by the substrate before it began to cool. For the subsequent stencils, temperature readings were taken immediately after the light was removed. These readings are shown in Table 89 below.

Table 89. Painted-At tag Temperature Readings

Time	Temperature
0 minutes	84° F
1 minutes	108° F
2 minutes	109° F
3 minutes	110° F
4 minutes	114° F
5 minutes	120° F
6 minutes	122° F
7 minutes	126° F
8 minutes	126° F
9 minutes	124° F

10 minutes (after light removal)	132° F

Cure was then begun on the Star & Bars stencil. The same procedure was utilized, with the lamp moved into position while still powered on with the shutters closed. After the standoff distance had been verified to be 10" using a measuring tape, the shutters were opened and cure was begun. Figure 44 shows the cure of the Star & Bars.

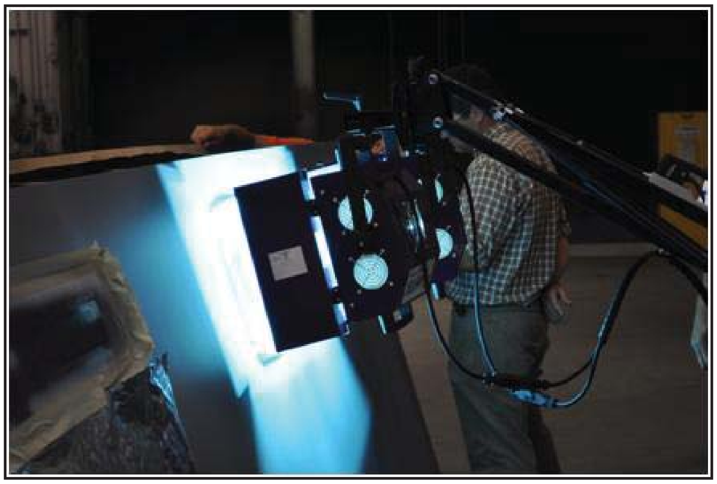


Figure 44. UV Cure of Star & Bars

While the Star & Bars stencil was curing, the Painted-At Tag was allowed to cool. It was allowed five minutes of cool-down time to a temperature of 100° F before the maskant was removed. Figure 45 shows the maskant removal occurring and Figure 46 shows the complete revealed stencil.

Figure 45. Maskant Removal of Painted-At Tag

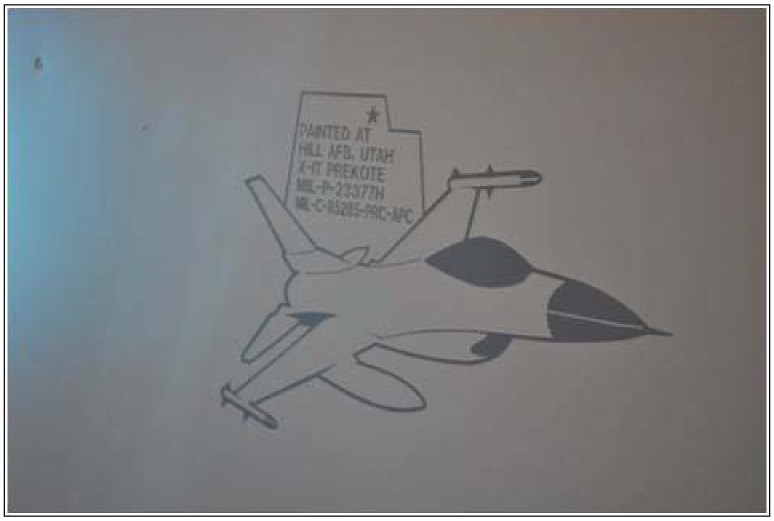


Figure 46. Completely Revealed Painted-At Tag Stencil

Maskant removal was completely successful, with no peel-away of the coating. However, a problem was detected at this point. The technician demonstrated smudges on his gloves, indicating that the coating was not completely cured despite exposure to UV light. After discussion, various personnel involved in the demonstration began pressing their fingers on the stencil to verify this. The coating was reported as feeling tacky and soft, definitely undercured. Pressure on the stencil surface left fingerprints.

After ten minutes, the cure time for the Star & Bars was complete and the lamp was moved on to the Rescue Arrow using the same procedure. Figure 47 shows the cure of the Rescue Arrow. Note that a metallic foil was placed beneath the Rescue Arrow stencil. This was done to simulate actual on-aircraft procedure, where a reflective foil is utilized as part of the maskant material in F-16 stencil processes.

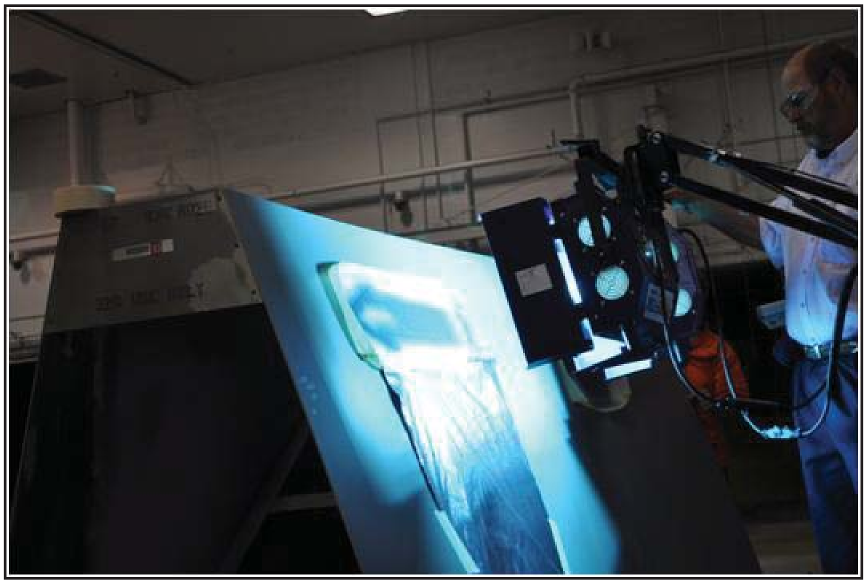


Figure 47. UV Cure of Rescue Arrow Stencil

H&S took UV measurements of the light reflected by the foil and reported extensive reflection of UV light, suggesting that use of reflective foil should be discouraged in UV-curable painting operations.

The Star & Bar showed a temperature reading of 138° F after removal of the light. A cool-down time of nine minutes was allowed before maskant removal, at which time the surface temperature was 90° F. Maskant removal for the Star & Bars stencil is shown in Figure 48.

Figure 48. Maskant Removal from Star & Bars

Once again, the state of cure was tested using subjective tactile means. As with the Painted-At Tag, the stencil felt tacky and under-cured. Fingerprints could be left in the stencil surface with sufficient pressure. Figure 49 shows this phenomenon visually.

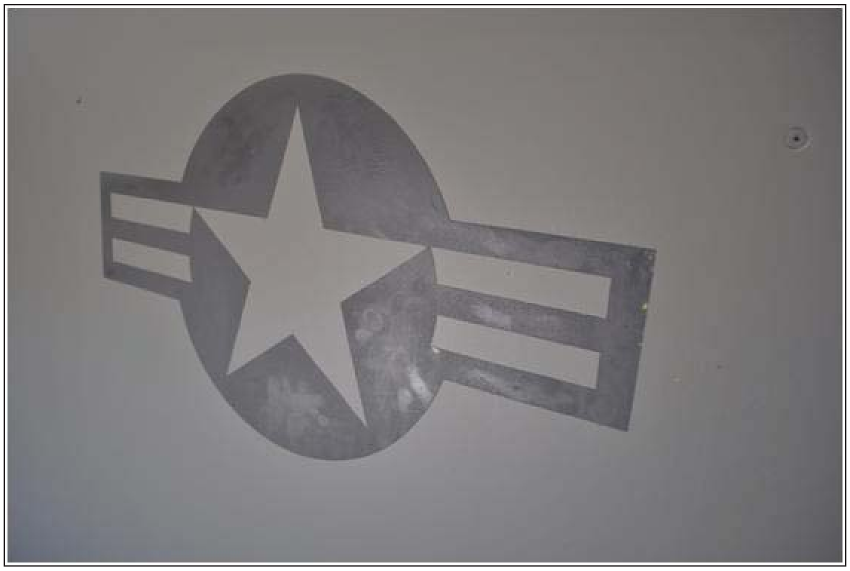


Figure 49. Prints Left in Stencil

At this point, the question was raised as to whether the coatings were somehow being underexposed to sufficient UV energy. In an attempt to achieve superior cure, the UV light was left over the Rescue Arrow for a full fifteen minutes of UV exposure. After removal of the light, the substrate temperature was recorded as being 132° F. As with the other stencils, the maskant material was successfully removed without any stencil peel-away.

After another subjective tactile inspection, the Rescue Arrow was reported as feeling ‘better’ than the other two stencils. However, it still evinced the same sense of tackiness (to a lesser degree) and did not feel fully cured. At this point it was concluded that the team would be unlikely to proceed to Dem/Val on the Buckley F-16.

The lamp was then moved back to the Star & Bars stencil, and the stencil was exposed to the UV light for an additional 5 minutes in an effort to improve state of cure. The additional UV exposure did not appear to improve the condition of the coating.

As a follow-up later in the day, gloss and dry film thickness readings were taken on those stencil areas large enough to allow it. The Rescue Arrow could not be recorded in this manner due to the stencil lines being too narrow, and only DFT readings could be taken on the Painted-At tag. Readings are shown in Table 90, with multiple readings taken for each measurement.

Table 90. Stencil Gloss and DFT Readings

Location	Gloss @ 60°	Gloss @ 85°	DFT (mils)
Star & Bars	5; 5; 5	16; 12; 16	5.3; 5.3; 4.4; 4.3; 4.9; 4.8; 4.5
Painted-At Tag	N/A	N/A	3.3; 2.9; 3.4

Topcoat Demonstration
In an attempt to determine if this problem lay solely with the UV 36118 paint, the team proceeded to apply UV 36173 paint to the taped-off area of the A-Frame Primed Surface. The paint shop technician applied the coating in quick passes, with pauses to take WFT readings during the application. Application occurred at 1323, approximately 22 hours after the primer was initially sprayed. During application, the technician expressed a concern that the coating was being applied unevenly and that he might end up with too thick an application in some spots if he made additional passes. BMS made the determination that for purposes of cure demonstration, a too-thin coating was more desirable than a too-thick coating and directed the technician to leave the coating on too thin.

Coating application on the A-Frame Primed Surface is shown as Figure 50.

Figure 50. UV 36173 Applied to Primed Surface

The cure area of the lamp utilizing both heads was determined to be a rectangle approximately 42” long by 18” high on a flat surface, with the light intensity being reduced near the edges of these areas. Based on this, six lamp movements were used to cure the 4.5’ by 4’ area of the topcoated surface over the course of an hour. Figure 51 shows the cure areas are labeled 1 through 6 to show the order in which they occurred, with 1 occurring first and six occurring last. The cure areas overlap slightly in the center of the A-Frame Primed Area, increasing the UV dosage that this area should receive.

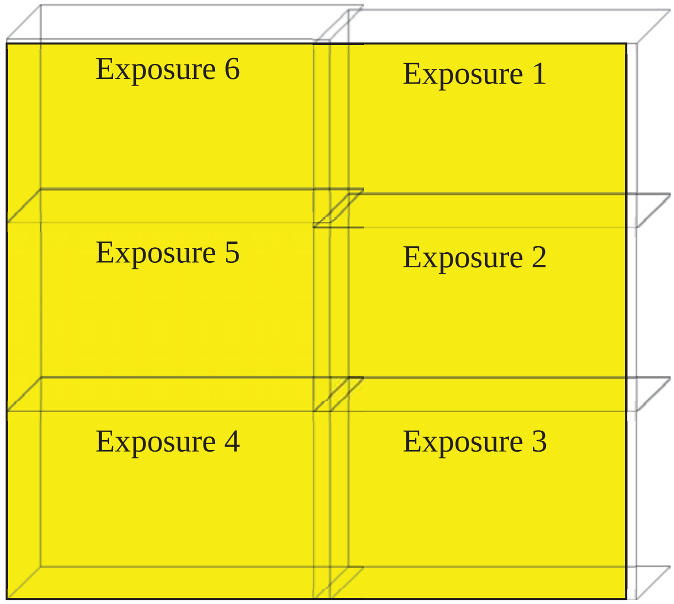


Figure 51. Cure Pattern of UV 36173 Gray Surface

Figure 52 shows the cure beginning in Exposure 1.

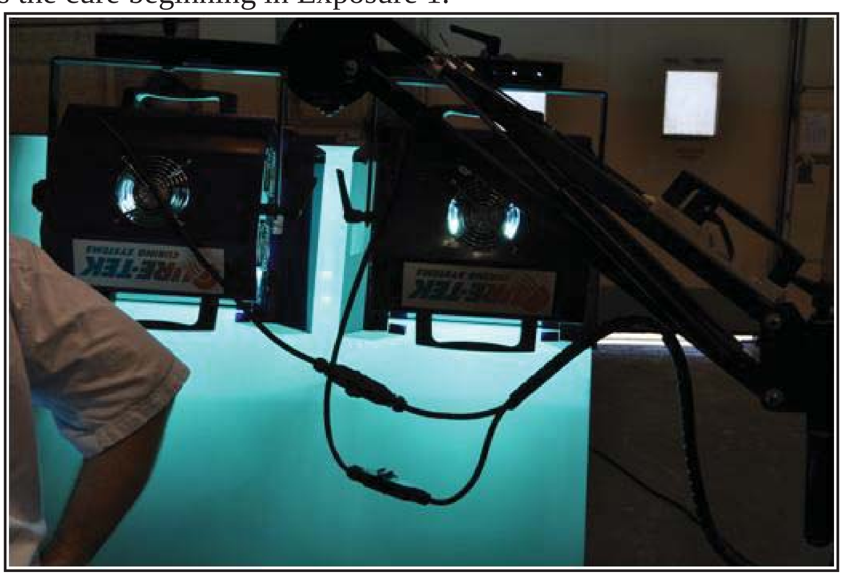


Figure 52. Cure of UV 36173 Gray on Primed Surface

The coating post-cure was extremely thin, and patchy. DFT readings at various places on the sprayed surface were taken as: 2.1, 2.1, 1.8, 1.4, 1.9, and 1.8 mils, meaning that in many cases the UV 36173 was less than a mil dry once the approximate 1 mil thickness of the primer is subtracted from the stack-up total. Furthermore, the coating exhibited the same tacky, not-cured feeling as the UV 36118 stencils. Pressing on the surface with fingers easily left marks. Figure 53 shows the cured UV 36173 surface.

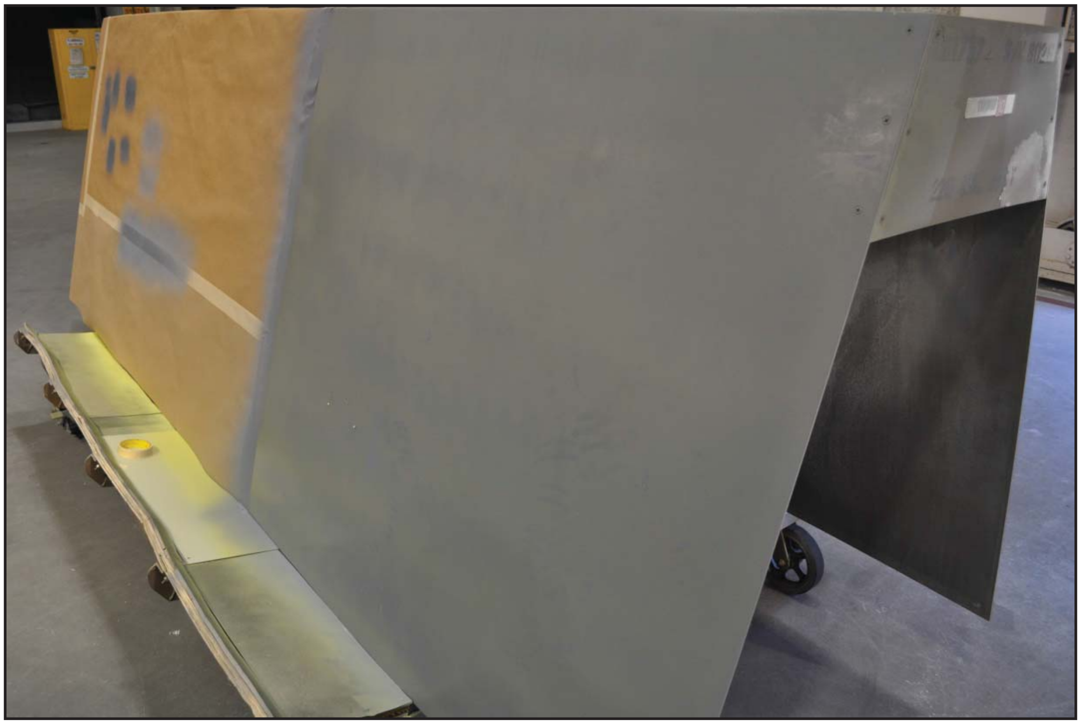


Figure 53. Cured UV 36173 Surface

In an effort to determine repeat the full cure results observed in the laboratory, a single bare aluminum panel of size 3” by 6” was obtained and painted with the UV 36118. It was laid horizontally on the floor and exposed to the UV lamp for 10 minutes at a 10 inch stand-off. The UV 36118 seemed to achieve a full cure, with none of the tackiness experienced by other post-cure examples. DFT measurements showed the coating averaged 0.6 mils thick on bare metal.

Post-Demonstration Discussion

The demonstration personnel cleaned up the site and returned to a conference room to discuss what had just been observed. The PI started out by saying that he viewed this as a learning experience and that no one should allow themselves to be discouraged by the roadblocks experienced that day.

Asked for input, BMS both expressed that the cure-out of the panel tested at the end meant that this batch and formulation was not inherently incapable of achieving cure. They advised that the team should map out some experiments to conduct the next day to try and determine the cause of the failure. CTC agreed that the results CTC had spraying and curing panels in laboratories are inconsistent with the results seen on the A-Frame. A number of potential causes of the failure were discussed, along with plans for the next day.

<ins>Greenness of Undercoat</ins>

Deft expressed a concern that the APC surface on which the stencils were painted was still green enough (the UV coating being sprayed approximately 15 hours after the APC was sprayed) that it was emitting isocyanates that were interfering with the UV cure processCTC and the PIcautioned that if that is the cause, it is an unacceptable result. One of the major benefits of UV-curable coatings is process time reduction, and the facility must be able to apply the stencils at least as soon as the current stencil coatings are applied. Deft suggested a possible solution of using a Prekote wipe on the APC before applying the stencil coating, and the team agreed to attempt that the next day. CTC noted that CTC has experimented in the past with applying Deft UV stencil coatings to APC coats less than 24 hours old, and no problems were experienced with cure. These stencils were applied to small panels.

Thinness of UV 36173 Topcoat

As noted, the UV 36173 coating was applied and cured extremely thin, not achieving full coverage of the primer coating beneath. It was possible that this did not given a true picture of how the 36173 is behaving. The team agreed that the following day selected sections of UV 36173 would be sprayed at increasing thicknesses (targeting 1, 2, and 3 mil DFT) to observe the behavior of the coating at its correct thickness. Based on the wet film thicknesses recorded on Wednesday, the WFT should be approximately twice the eventual DFT desired.

It should be noted that the UV 36118 stencils were applied at the manufacturer-recommended thickness, so coating thickness cannot explain the anomalies seen in the stencils.

Testing of UV 37038 Black Coating

The third color, UV 37038 black, was not applied and cured on Wednesday. The black performed the best of the three coatings in the laboratory testing performed at Battelle, and it was deemed desirable to spray and cure a section of black for purposes of comparison. It was decided to spray and cure a 1 foot by 1 foot section of black as stencil coating on the A-Frame APC side the next day.

PPG Primer and Topcoat

Hill uses MIL-PRF-23377 primers and MIL-PRF-85285 topcoats supplied by PPG coating. All topcoats and primers used in laboratory testing were supplied by Deft Coatings. It was suggested that there may be compatibility issues with PPG coatings. However, such issues would be unacceptable as the Deft UV-curable coatings must be compatible with what Hill AFB is actually using. In addition, coating compatibility issues would more likely cause adhesion issues rather than state of cure issues.

Size/Temperature of Substrate

CTC noted that the temperatures recorded for the A-frame were substantially lower than the temperatures recorded during other cure experiments. This may be due to the fact that the A-frame substrate is thick (.09 inches) and large, allowing heat to be conducted through the whole structure and radiated away from a large surface area. Temperatures recorded during cure did not exceed 140° F, while CTC has recorded temperatures in excess of 180° F on large composite structures and small aluminum panels exposed to a 1200W lamp. If the coating formulation is dependent on a thermal component for cure, then the lack of sufficient heat might be hindering cure. If this is the case then it must be considered a formulation issue, as the A-frame exposure is representative of the heat that will be achieved on an actual aircraft surface, and it is desirable to limit heating of aircraft surfaces in any case.

However, Deft and BMS representatives stated that there is no intent that the coating should depend on a thermal cure and they did not deliberately include such a requirement in its design. CTC noted that CTC has successfully cured Deft UV 37038 Black as a stencil on relatively large aluminum structures (several feet in diameter), though this was using a previous material batch and the temperature was not recorded at the time.

<u>Lamp Output</u>
BMS and Deft typically use a 400W H&S Autoshot lamp in their UV laboratory activities, as opposed to the 1200W lamp head used for each of the two heads of the Demonstration Lamp. The 400W unit is more intense directly under the light for a single panel cure, though possessing less effective cure area. Furthermore, the extremely long extension cords used on the Demonstration lamp on Wednesday might be causing a further drop in UV energy output. H&S stated that in measurements that day he had noticed a slight drop in their usual output energies, but not a drastic drop.

UPDATE: The following week H&S provided data taken from a 400W unit in their lab, a 1200W unit in their lab, and data taken out at Hill. This data was taken with H&S's special UVA-only light meter that excludes anything outside the UVA portion of the spectrum and hence cannot be compared directly with measurements CTC has taken in their lamp studies, which include the small portion of the UVB spectrum that the H&S lamps emit. However, the H&S data can be compared against itself. H&S's reporting is included as Table 91 below.

Table 91. H&S Reported Irradiance

Lamp & Stand-Off	Power	% of regular 400W power
400W @ 10 inches	39mW	100%
1200W @ 10 inches, no extension cord	31 mW	79%
Demo lamp data recorded at Hill AFB	23mW (left head) / 25mW (right head)	59% / 64%

However, CTC has successfully achieved cure of the prior batch of Deft UV 37038 black coating in our laboratory, using a 1200W lamp at 10 inches stand-off for 8 minutes. Moreover, one of the UV 36118 Gray stencils was exposed to 15 minutes of curing energy and still failed to achieve effective cure. It does not seem like the energy drop-off on the lamp was sufficient that the coating would never achieve cure.

<u>Temperature and Humidity</u>
It was observed that Hill AFB experiences an unusually high temperature and low humidity as compared to other areas of the country. It is possible that no coating development and/or testing has been conducted extensively duplicating this environment. The team had not obtained the

temperature and humidity of the F-16 paint bay that day, but they resolved to do so the next day. Again, if the coatings will not function at Hill AFB environmental conditions, they must somehow be made to do so.

However, environmental testing was a specific component of the laboratory testing under the Joint test Plan, and the three deft UV colors were coated and cured at 90°F and 20% Relative Humidity (RH) in a specially controlled environmental chamber using a 1200W lamp. Cure was successfully achieved, and no similar 'tackiness' problem was observed. The data from wet tape and crosshatch testing performed on the panels cured at those conditions had not yet been obtained from Battelle, and CTC agreed to make arrangements to receive it as soon as possible.

<u>Other Discussion</u>
The team resolved to do cross hatch adhesion and pencil hardness tests on the stencils painted Wednesday in order to determine their state of cure in a more effective manner. UPDATE: The next day it was determined that the aluminum of the A-Frame had not received any pretreatment before the primer was applied, and hence all adhesion failures in crosshatch adhesion testing would fail at the substrate, making the crosshatch test ineffective.

BMS confirmed that the grays and black are all based on the same resin system and should not have radically different performance properties. Deft confirmed that the formulations should match those applied and cured during the laboratory testing at Battelle, except that the 36173 and 37038 have had anti-sag agents, a new dispersant, and an agent to prevent pigment float (in the case of the 36173) added.

July 15, 2010

Morning Demonstration Efforts
The team returned to the F-16 paint bay at 0800 on Thursday morning. Several team members had to leave Wednesday evening, leaving CTC and Deft in addition to the Hill personnel. No one remained from BMS or H&S Autoshot.

Upon return, the first thing the team did was reexamine the stencils. They seemed slightly improved but were still soft and tacky. Deft observed they felt rubbery and stated, "I can move the paint around on the surface with my finger." CTC and Deft made comparisons to the feeling of a two-component system that had been shorted its proper amount of catalyst and not had enough to achieve full cure. The 36173 topcoat area was also reexamined, and cure seemed to vary over the surface with many areas still feeling sticky and tacky.

At 0848, CTC received an environmental sensor for temperature and RH from the paint shop crew. CTC measured the temperature as being 72°F and the RH as being 42% within the paint bay. This seemed like an unusually high humidity, and when the sensor was taken outside the humidity reading immediately dropped to 29%. Questioning the paint booth crew, the team found that the humidity in the booth was being artificially raised to accommodate a special coating system that required a high RH. This did not occur the previous day, and RH on Wednesday in the booth was likely closer to the outside reading of 29%.

NOTE: All painting and curing activities conducted on Thursday were wherefore done in a near-specification temperature and humidity environment. Given the results below, temperature and humidity do not appear to be major contributing factors to the coating failure.

Two wipes were tried on the 36173 topcoat area, the first using a rag soaked with methylene chloride and the second using a rag soaking with isopropyl alcohol. In each case, the wipe easily removed coating from the surface.

<u>A-Frame Primed Surface Painting</u>

The area of the A-Frame Primed Surface which had been covered the previous day was opened up, and three squares each 1-foot by 1-foot in area were taped off. The UV 36173 paint was shaken and applied to these areas in varying thicknesses, with the thickness checked using a WFT gauge. Application of the UV 36173 coating occurred 0914 to 0917, approximately 42 hours after initial application of the primer.

WFT were checked as follows:

- Area 1 – 3 mils (one pass to apply)
- Area 2 – 5 mils (two passes to apply)
- Area 3 – 6 to 7 mils (3 passes to apply)

The areas were given a 15 minute solvent flash-off time before application of the UV light. However, approximately 7 minutes after application the team started to observe coating sag visible to the naked eye. For all three areas (though less so on the lightly coated Area 1), the coating applied to the near-vertical surface of the A-Frame gradually began to flow down the side. Moreover, Deft stated that the coating pigment was actually starting to pull from the rest of the coating in a phenomenon referred to as “flocculation”. This matched observation of a high degree of blue pigment floating on the surface of the UV 36173 when it was opened for inspection before being mixed.

Each area was then exposed to UV light for ten minutes at a ten inch stand-off distance. Because of the smaller area of exposure, only one lamp head was powered on and utilized. Because of this, power could be obtained directly from the outlets at the back of the paint booth, vastly reducing the length of the required extension cord. Only one area could be exposed at a time, so Area 1 began exposure 15 minutes after coating application, Area 2 was exposed at 27 minutes after coating application, and Area 3 was exposed at 38 minutes after coating application. Though unintended, this means that the thicker the coating application, the more it was allowed to sag.

Figures 54, 55, and 56 show each area as it appears post-cure.

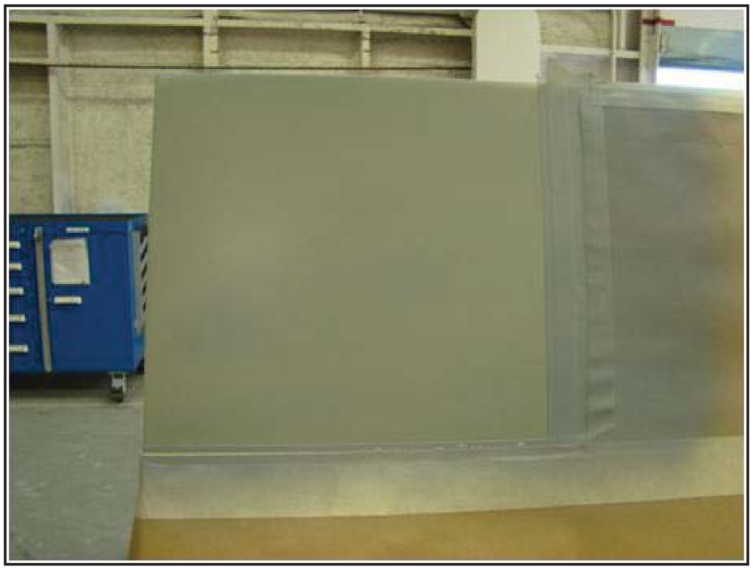


Figure 54. UV 36173 Area 1 Post-Cure

Figure 55. UV 36173 Area 2 Post-Cure

Figure 56. UV 36173 Area 2 Post-Cure

Post-cure DFT readings were taken of each area. On Area 1, sag was minimal due to coating thickness and a consistent reading 2.6 mils was recorded for the coating stack-up. On Area 2, readings for the coating stack-up ranged from 2.7 mils in the upper areas to 4.6 near the bottom where all the coating had flowed to. On Area 3, readings were 5 mils at the bottom and varied in the extreme elsewhere on the surface.

A-Frame APC Surface Painting

Previously covered areas of the A-Frame APC surface were uncovered and taped off into three 1-foot by 1-foot squares. They were painted as follows:

Area 1:

- DFT of APC surface pre-spray = 3.3 mils
- Painted with UV 37038 Black at 1014 (approximately 35 hours after APC application)
- Wet Film Thickness reading of 3 to 4 mils
- Cured 10 minutes at 10 inches
- DFT post cure = 5.6 mils
- Gloss Post-Cure = 5 @60° and 12.4 @85°

Observations Post-Cure: The coating was left to sit for 20 minutes before any attempt was made to ascertain its state of cure, in order to allow time for it to completely cool. While not as tacky as the other stencil coatings, there was still some slight rubbery feeling to the coating. It felt very soft, though you could not leave thumbprints in it. Figure 57 shows the area post-cure.

Figure 57. UV 37038 Black Area 1 Post-Cure

Area 2:

- DFT of APC surface pre-spray = 3.3 mils
- Painted with UV 36118 Gray at 1027 (approximately 35 hours after APC application)
- Wet Film Thickness reading of 3 to 4 mils
- Cured 10 minutes at 10 inches
- DFT post cure = 5+ (difficult to measure due to coating softness)
- Gloss Post-Cure = 15 @60° and 19 @85°

Observations Post-Cure: The coating was left to sit for 12 minutes after removal of the light before any attempt was made to ascertain its state of cure. It was very soft and rubbery, and it seemed worse than the black. Figure 58 shows the area post-cure.

Figure 58. UV 36118 Area 2 Post-Cure

Area 3:

- DFT of APC surface pre-spray = 4 mils
- 100% mixture of Prekote wiped onto surface and then wiped off with rag before coating application*
- Painted with UV 36118 Gray at 1030 (approximately 35 hours after APC application)
- Wet Film Thickness reading of 3 to 4 mils
- Cured **20** minutes at 10 inches*
- DFT post cure = 6 (difficult to measure due to coating softness)
- Gloss Post-Cure = 15 @60° and 19 @85°

*Notes: This Area was wiped with Prekote before curing in order to attempt to flush out any remaining isocyanates, as per the discussion the previous day. In addition, cure time was extended to a full 20 minutes in a last ditch effort to achieve some coating cure.

Observations Post-Cure: Too aggressive a mixture of Prekote was used; the team were later told that a dilution of 10% Prekote and 90% water would have been more the usual practice. Because of this, the coating seemed to form an "orange peel" effect and slightly separate. However, the increased exposure time seemed to improve the ‘feel’ of the coating’s state of cure. No picture is available.

Pencil Hardness

Pencil hardness testing was conducted on all three areas. Results were as follows:

- Area 1 (37038 Black): 3B Pencil Hardness
- Area 2 (36118 Gray): <5B Pencil Hardness
- Area 3 (36118 Gray cured 20 minutes): <5B Pencil Hardness

Analysis: This seems to confirm the subjective tactile impressions of the demonstration team. Even the 37038 Black, the least tacky-feeling of the three coatings, cannot be called truly cured at a hardness of 3B.

Viscosity

The team tested the viscosity of the UV 36173 coating in a #4 Ford cup and found it took approximately 34 seconds to drain.

Off-Site Coating Testing

CTC utilized a coating formulator at the CTC Johnstown facility and checked the Deft UV coating samples at that location. It was confirmed that the most recently received samples were from the same batch as were utilized in demonstration, and he sprayed out a sample of each color on bare panels. The same sag and pigment separation issues were evident with our sample of the 36173 coating.

In addition, the formulator in Johnstown cured a sample of the new batch of UV 37038 Black and compared it to a sample from an older batch of UV 37038 Black. It was reported that the newer batch seemed to achieve a poorer and more incomplete cure under the same light.

APPENDIX G - ROOT CAUSE ANALYSIS TESTING

Deft Coating Testing

Cure Parameters

Deft cured all samples with a 400W H&S Autoshot Cure-Tek Lamp for 8 minutes at a distance of 12 inches. A Cure-Tek 1200W lamp was placed on order for further development work.

Freeze-Thaw Stability Testing

Deft tested samples of the UV-curable topcoats after putting them through a freeze-thaw cycle to test storage stability. Note that these samples were taken from retains of batches 200-63, 200-64, and 200-65; the same batches tested at Hill AFB. The retains were taken before the Hill samples were shipped out and have never left the Deft laboratory.

Deft reported that when the freeze-thaw samples were cured, they were at a pencil hardness of approximately HB. This is notably softer than the retain samples cured without passing through the freeze-thaw cycle, which achieved a pencil hardness of approximately 2H. It does appear that a freeze-thaw cycle is having an effect on the coatings. When examining these cycles under a microscope, Charles discovered another phenomenon (discussed as “Micro-Voids” below).

Testing of Sample Returned from Hill AFB

Coating samples utilized during the attempted demonstration at OO-ALC were returned to Deft for comparison testing with the retains. The samples returned from Hill had hard-packed (meaning that the pigments had settled and tightly packed themselves at the bottom of the paint can) and required one hour of time on the paint shaker to return the pigment to proper dispersion. By comparison, the samples which were retained at Deft were easily incorporated by stirring with a stick. Regarding whether failure to shake the coatings long enough could have contributed to the Dem/Val failure out at Hill AFB, Deft noted that a lack of pigment should help the coating cure, not make cure more difficult to achieve.

When shaken and cured as noted above, the samples did achieve a ‘cured’ state (that is, non-tacky, seemingly hard). However, their pencil hardness measured as 5B compared to the 2H of the retain samples. The fact that the coatings were able to be brought to a non-tacky state, even if pencil hardness suggests that they are not fully ‘cured’, may be due to the less intense UV exposure (1200W versus 400W, extension cords in use) at the Hill AFB Dem/Val.

Deft concluded that something might have happened to the Hill AFB samples since they left Deft the first time. They speculated that this may be related to the instability seen in the freeze-thaw cycle samples, with whatever reaction is occurring somehow accelerated.

Coating Micro-Voids

When examining the freeze-thaw cycle samples under X100 microscope, personnel at Deft observed “what I can only describe as micro-craters or voids”. These were small pits on the surface of the coating that are also described as looking like “swiss cheese”. It almost looked like pockets of material in the coating were simply being burned away by the UV light.

Retains of every batch of UVA curable topcoat that has been prepared to date of each of the three colors of paint were sprayed for comparison testing. The voids were present in some samples but not others, the common factor being that all samples with voids had the sag resistance additive and the dispersing additive which stabilizes the pigments and prevents them from settling in the can upon storage. One or both of these ingredients may have reacted with other components in the paint.

Both of these agents were added to the formulation after Bayer completed its initial formulation effort. They were added in response to observations made during the spray-out for JTP testing at Battelle Memorial Institute. Note that the 21BK003 (37038 Black) and the 21GY001 (36173 Gray) coatings shown in the Battelle data do not contain these additives, as they were sprayed and cured before the addition to the formula. The 21GY002 (36118 Gray) coatings shown in the Battelle data do contain both agents.

To verify that this is a chemical interaction as opposed to a physical heat reaction, samples of both additives were placed in an oven at a high temperature above that of the substrate when illuminated by the UV lamp. There was no loss of mass, making it unlikely that this is a detrimental reaction to heat.

<u>Correction Plan for Micro-Voids</u>

To determine which additive (or if both additives) are causing the micro-voids, Deft prepared three small sample batches of coating (either 21GY001 or 21GY002). One batch omitted the sag resistance additive, one batch omitted the dispersant (replacing it with the dispersant used in Bayer's original formula), and one batch omitted both the sag resistance additive and replaced the dispersant.

BMS Coating Testing

Personnel at Bayer Material Science conducted testing to determine if cure of the coating was being affected by temperature. The coating tested was obtained from the same batches formulated for the OO-ALC demonstration.

<u>Application and Cure Parameters</u>

- Primer - 1.0 – 1.3 dry mils Deft's 02Y40B allowed to dry for 4 hours ambient
- Both gray topcoats 1.0 dry mils
- Black topcoat 2.0 dry mils
- Cured under 1200W Autoshot lamp - 10 inches, 8 minutes
- Fan / dry ice used to control temperature
- Small particles observed in all topcoats after spraying

Figure 59 shows the results.

Deft Formulation	Cure Conditions	Surface of Coating	MEK Double Rubs	Pencil Hardness
36173	High Fan, 133 F	Slightly Tacky	10	3B
36173	Low Fan, 160 F	Slightly Tacky	6	4B
36173	No Fan, 190 F	Tacky	6	4B
36173	Dry Ice	Tacky	7	4B
37038	High Fan, 133 F	Slightly Tacky	50	B
37038	Low Fan, 160 F	Slightly Tacky	80	B
37038	No Fan, 190 F	Not Tacky	37	B
37038	Dry Ice	Tacky	>100	3B
36118	High Fan, 133 F	Tacky	6	4B
36118	Low Fan, 160 F	Slightly Tacky	6	5B
36118	No Fan, 190 F	Tacky	6	3B
36118	Dry Ice	Tacky	10	3B

Figure 59. BMS Testing of Effect of Temperature on Cure

As shown, temperature appeared to have little effect on coating cure.

CTC Work

Cure Intensity

CTC evaluated if the failure to cure might have been caused by varying intensity of UV light during the demonstration. CTC had identified that the intensity of UVA exposure under a 1200W H&S Autoshot lamp unit varied greatly within the cure area directly underneath the lamp head. Samples of the UV-curable coatings were cured at varying intensities and then tested to determine their state of cure.

Coatings Evaluated:

CTC evaluated the coatings listed in Table 92. A previous batch of the 37038 black, formulated in 2009 and tested at Battelle, was used as the control coating. Its performance was compared to the coating batches demonstrated at Hill to determine if there is a difference in performance between the previous and current coating batches.

Table 92. Batches Used in CTC Cure Testing

Deft Identification	Color	Batch Number	Description
21GY001	36173 Gray	200-63	Hill AFB batch; formulated June 2010
21GY002	36118 Gray	200-64	Hill AFB batch; formulated June 2010
21BK003	37038 Black	200-65	Hill AFB batch; formulated June 2010
21BK003	37038 Black	200-61	Previous batch formulated October 2009 (control coating)

Panels and Coating Stack-ups Utilized:
One panel was created for each topcoat. The panels were 2024-T3 temper aluminum of dimensions 12"x 12" painted with a MIL-PRF-23377 primer which was allowed between 20 and 24 hours of cure time. The primer was applied to a dry-film thickness of 0.6 to 0.9 mil. The UV-curable topcoats were applied at a dry-film thickness of 1.7 to 2.3 mil. Application and curing were conducted with the panel in a horizontal position, to avoid introducing the effect of any coating sag in the current formulation.

UV Energy Exposure:
During the Dem/Val, the cure area was considered to be approximately 42" long by 18" high for two lamps heads, which would translate to approximately 18" by 18" for a single lamp head (taking the overlap between the two heads into account). As per other measurements taken, the UVA intensity appears to be approximately the same distribution across each quadrant of the cure area. That is, the upper left quadrant from the center has a light distribution similar to the lower right quadrant, which is similar to the upper right and lower left quadrant. Accordingly, each test panel was to be cured within the upper left quadrant as being representative of all light intensities found beneath the cure area, as shown below in Figure 3. The stand-off from lamp surface to substrate was ten inches, to duplicate the Dem/Val procedure.

Cure Pattern Utilized:
Each panel was placed in the upper left quadrant of the H&S 1200W lamp cure area. It was then subdivided into six distinct evaluation areas, as shown in Figure 60 below.

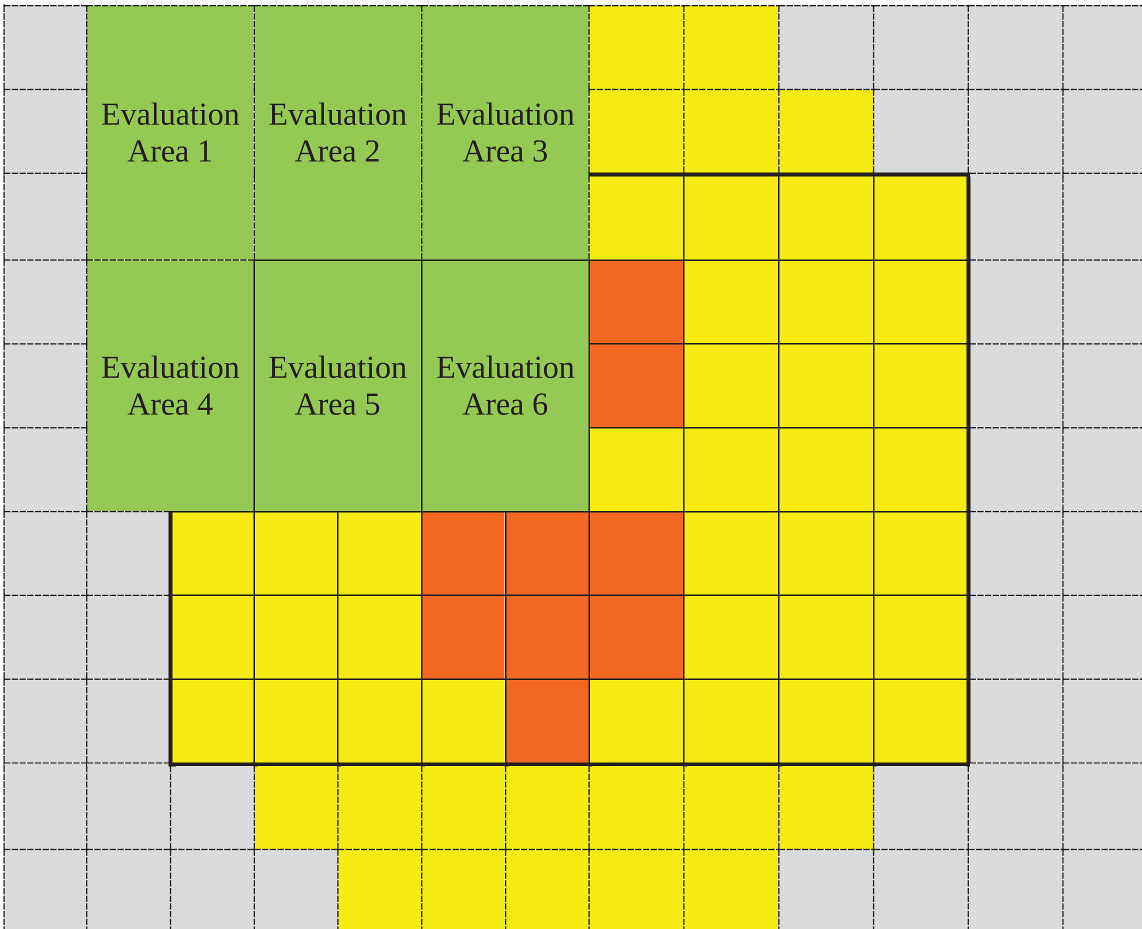


Figure 60. Cure Test Pattern

As shown in Figure 61, each 12” by 12” panel was divided up into six evaluation areas. The intensity of UV light in each area was measured as maximum UVA milliwatt (mW) readings detected using a Solar Light model PMA2100 Meter with a PMA 2110F UVA Detector probe, was recorded separately for each panel. Despite efforts to place each panel in exactly the same position and stand-off distance from the lamp, minor variations in mW readings for the same spot on different panels were recorded. Exposure was for a duration of 10 minutes at a stand-off distance of 10 inches from the substrate, as per Dem/Val procedure.

State of Cure Testing:
Two were utilized to determine State-of-Cure:

- MEK Double-Rub
- Pencil hardness

The MEK double-rub was 50 double-rubs. Subjective observations as to the amount of coating coming off onto the rag were recorded, even if no primer is exposed. The MEK double-rub was conducted in the center of each evaluation area, allowing pencil hardness readings to be taken along each evaluation area’s edge.

The pencil hardness test was conducted at two locations for each evaluation area, approximating the area of maximum power and minimum power based on the meter readings taken before beginning the experiment.

21GY001 Batch 200-63:
The 21GY001 was cured at a laboratory temperature of 70.9°F and a relative humidity (RH) of 53.7%. The intensity of UV light was measured five times in each of the six evaluation areas. Milliwatt readings of 55 or greater are shown as red; 36 to 55 are shown as orange; 15 to 36 are shown as yellow; and 0 to 15 are shown as gray. In addition, the surface temperatures before and after cure are noted next to each evaluation area. This is shown in Figure 61 below.

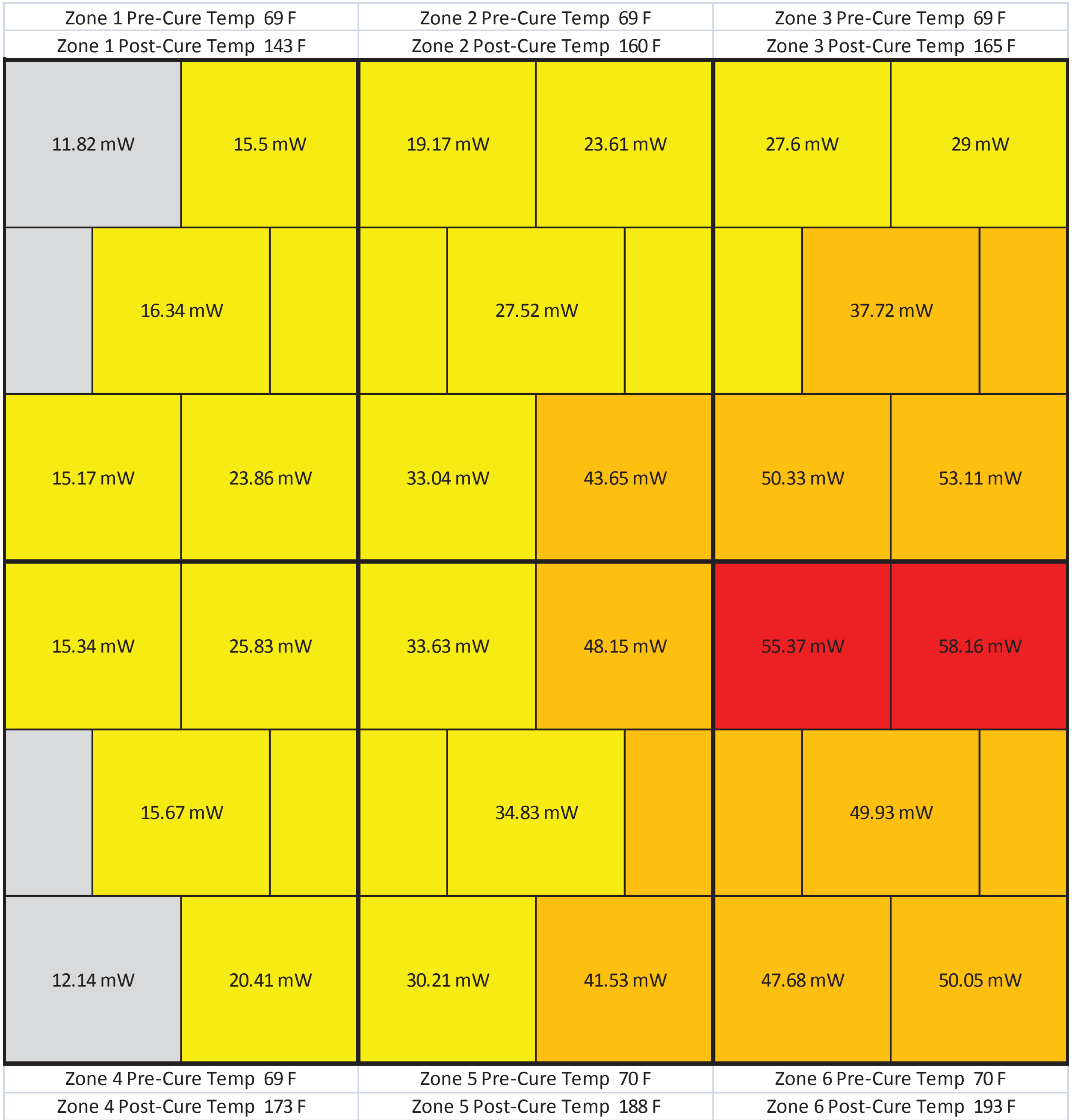


Figure 61. 21GY001 Batch 200-63 UVA Intensity

Two pencil hardness readings and an MEK double-rub resistance were taken for each evaluation area. When the primer was exposed, the number of double-rubs until primer exposure was noted. A notation of “coating gummy” indicates that though no primer was exposed after 50 double-rubs, the coating visibly smeared on the surface, came off on the rag, and otherwise indicates that it was being affected by the solvent wipe. The pencil hardness and double-rub measurements are shown in Figure 62.

Figure 62. 21GY001 Batch 200-63 State of Cure

21GY002 Batch 200-64:

The 21GY002 was cured at a laboratory temperature of 70.9°F and a relative humidity (RH) of 53.7%. The intensity of UV light was measured five times in each of the six evaluation areas. Milliwatt readings of 55 or greater are shown as red; 36 to 55 are shown as orange; 15 to 36 are shown as yellow; and 0 to 15 are shown as gray. In addition, the surface temperatures before and after cure are noted next to each evaluation area. This is shown in Figure 63 below.

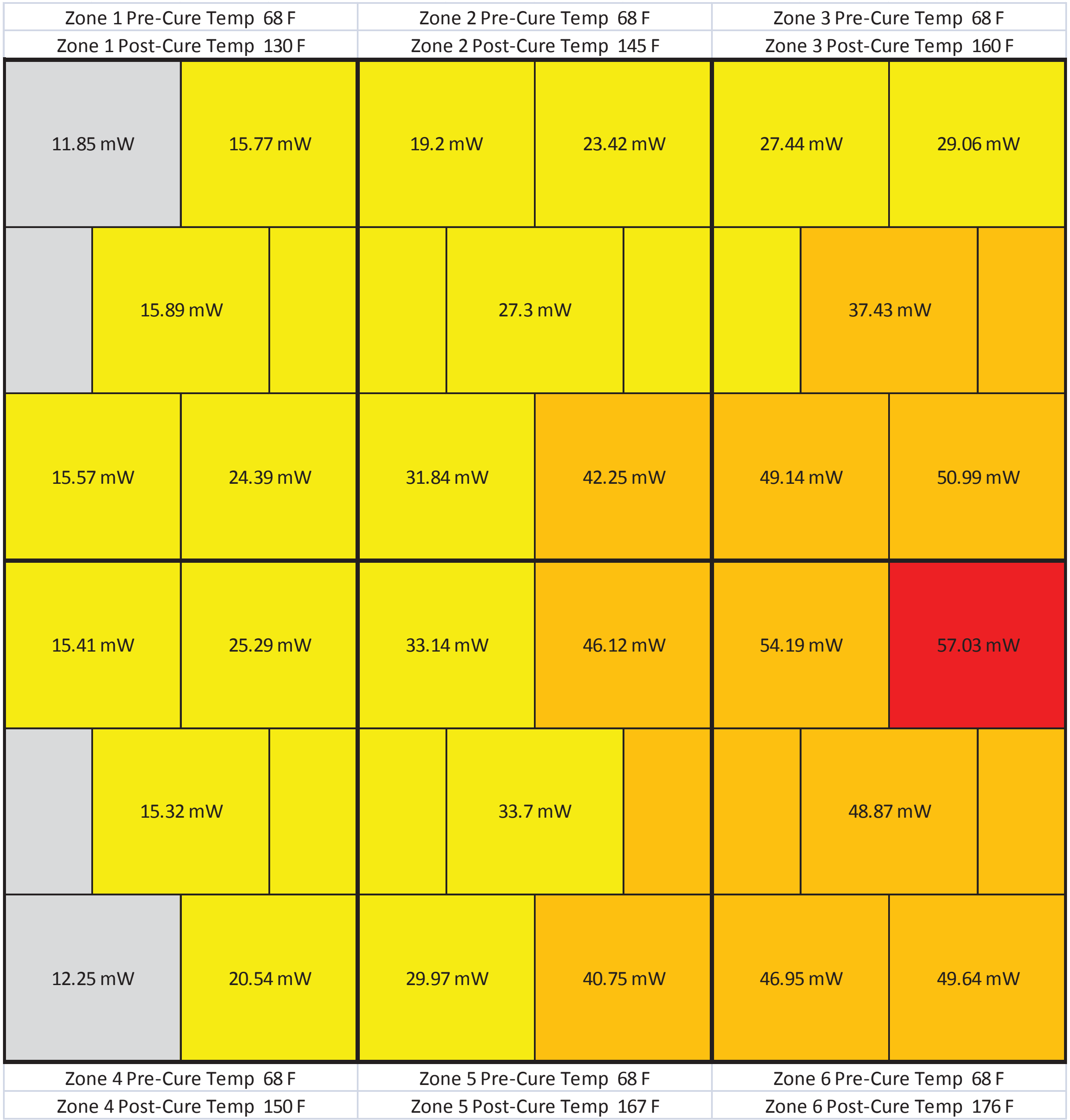


Figure 63. 21GY002 Batch 200-64 UVA Intensity

Two pencil hardness readings and an MEK double-rub resistance were taken for each evaluation area. When the primer was exposed, the number of double-rubs until primer exposure was noted. A notation of “coating gummy” indicates that though no primer was exposed after 50 double-rubs, the coating visibly smeared on the surface, came off on the rag, and otherwise indicates that it was being affected by the solvent wipe. The pencil hardness and double-rub measurements are shown in Figure 64.

Figure 64. 21GY002 Batch 200-64 State of Cure

21BK003 Batch 200-65:
The 21BK003 was cured at a laboratory temperature of 71.2 °F and a relative humidity (RH) of 52.6%. The intensity of UV light was measured five times in each of the six evaluation areas. Milliwatt readings of 55 or greater are shown as red; 36 to 55 are shown as orange; 15 to 36 are shown as yellow; and 0 to 15 are shown as gray. In addition, the surface temperatures before and after cure are noted next to each evaluation area. This is shown in Figure 65 below.

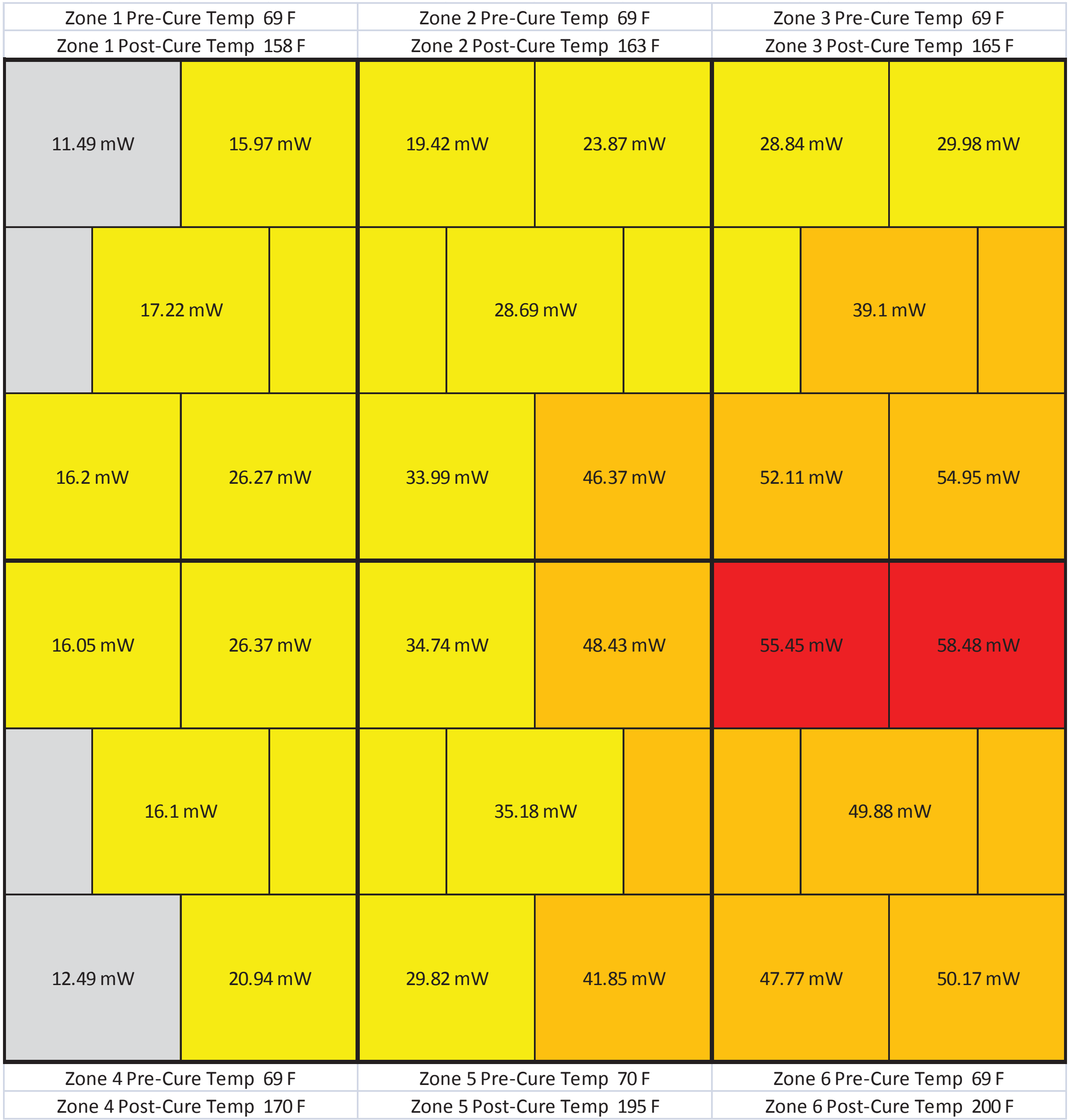


Figure 65. 21BK003 Batch 200-65 UVA Intensity

Two pencil hardness readings and an MEK double-rub resistance were taken for each evaluation area. When the primer was exposed, the number of double-rubs until primer exposure was noted. A notation of “coating gummy” indicates that though no primer was exposed after 50 double-rubs, the coating visibly smeared on the surface, came off on the rag, and otherwise indicates that it was being affected by the solvent wipe. The pencil hardness and double-rub measurements are shown in Figure 66.

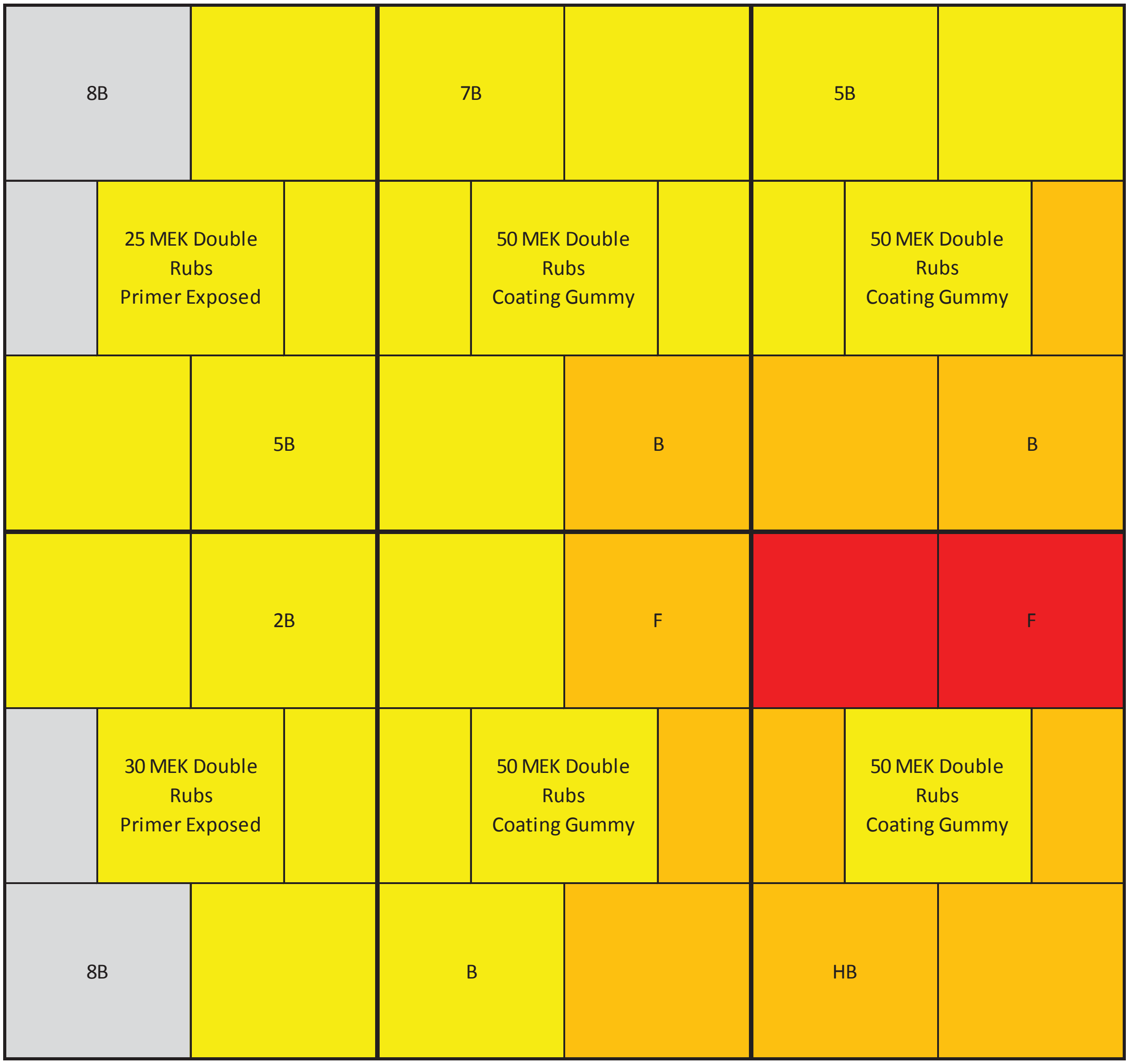


Figure 66. 21BK003 Batch 200-65 State of Cure

21BK003 Batch 200-61:

The 21BK003 was cured at a laboratory temperature of 71.1 °F and a relative humidity (RH) of 52.4%. The intensity of UV light was measured five times in each of the six evaluation areas. Milliwatt readings of 55 or greater are shown as red; 36 to 55 are shown as orange; 15 to 36 are shown as yellow; and 0 to 15 are shown as gray. In addition, the surface temperatures before and after cure are noted next to each evaluation area. This is shown in Figure 67 below.

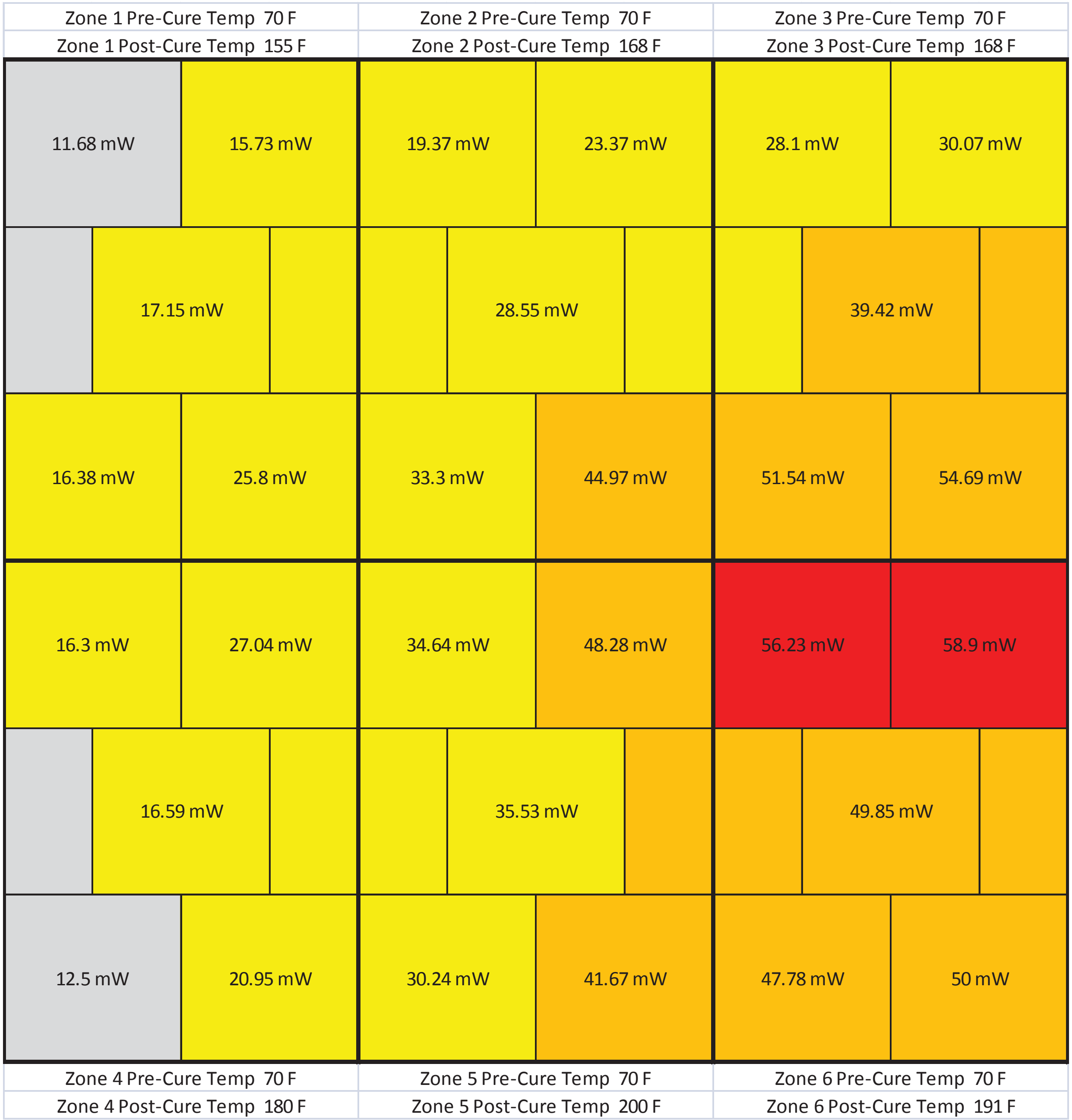


Figure 67. 21BK003 Batch 200-61 UVA Intensity

Two pencil hardness readings and an MEK double-rub resistance were taken for each evaluation area. When the primer was exposed, the number of double-rubs until primer exposure was noted. A notation of "coating gummy" indicates that though no primer was exposed after 50 double-rubs, the coating visibly smeared on the surface, came off on the rag, and otherwise indicates that it was being affected by the solvent wipe. The pencil hardness and double-rub measurements are shown in Figure 68.

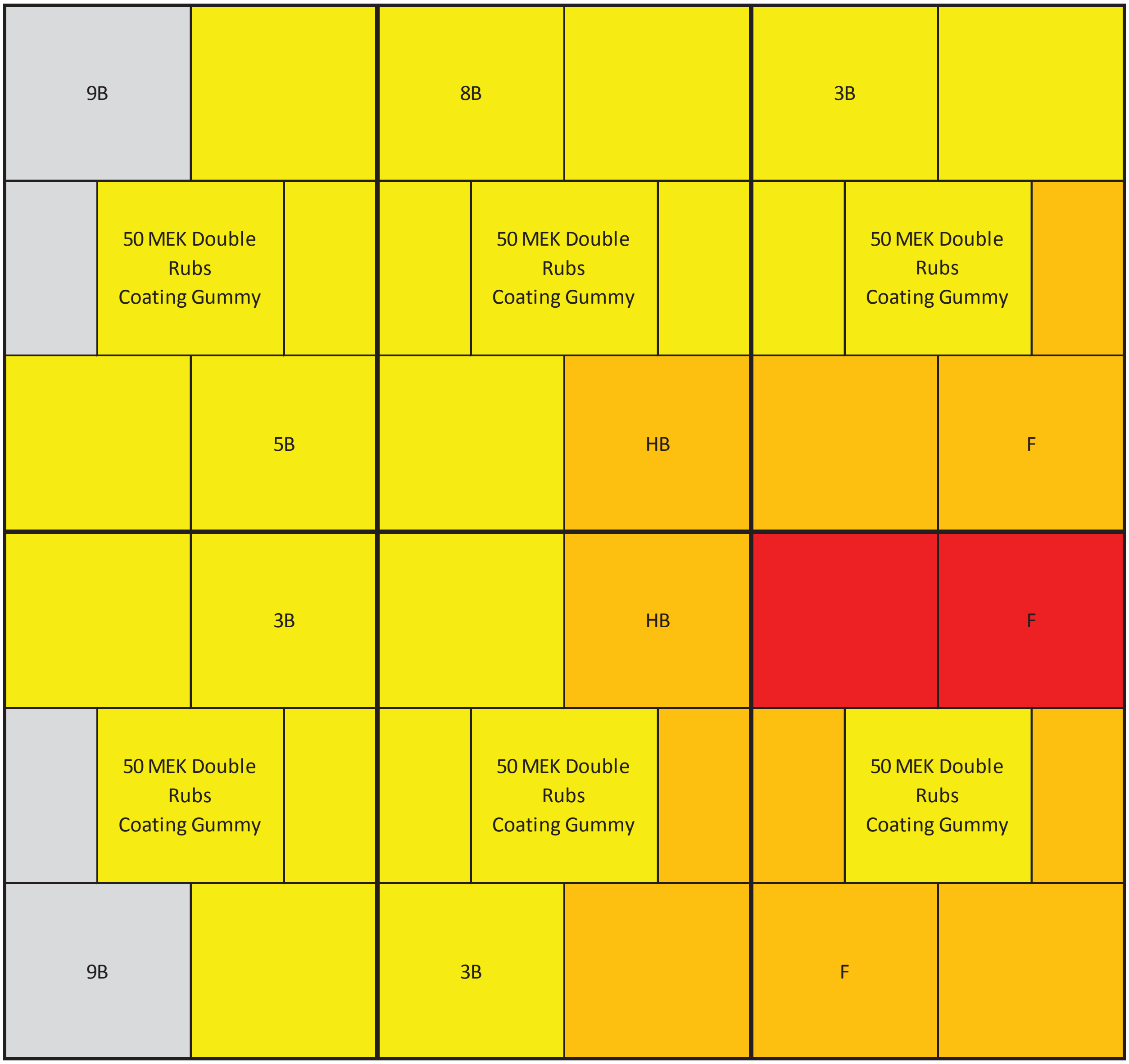


Figure 68. 21BK003 Batch 200-61 State of Cure

Conclusion

The black coatings showed a harder pencil hardness score at equivalent cure energies as compared to the gray coatings.

APPENDIX H - RESIN SCREENING DATA

Resin	Resin Ratios	Misc.	PH	Impact	Mandrel	MEK
U100			HB	<10	Pass	>100
U400		Fast Cure	4H	<10	Fail	>100
680H			H	<20	Fail	>100
XP2491		Tacky	<B	>40	Pass	>100
XP2513			F	<20	Pass	>100
XP2683			F	<10	Pass	>100
VP2266			F	<20	Pass	>100
G2235			H	<10	Pass	>100
G2280			B	<20	Pass	>100
G3414			H	<10	Pass	>100
G4316			B	<20	Pass	>100
G4425			H	<10	Pass	>100
8807		Fast Cure	F	>40	Pass	>100
8411		Tacky	<B	>40	Pass	>100
XP2491/U400	50/50		3H	<10	Fail	>100
XP2491/XP2683	50/50		B	<40	Pass	>100
XP2491/G2235	50/50		HB	>40	Pass	>100
XP2491/G2235/BYK370	50/50	Hazy	HB	>40	Pass	>100
XP2491/G3414	50/50		HB	>40	Pass	>100
XP2491/G3414/DOW51	50/50	Hazy	HB	>40	Pass	>100
8807/U400	50/50		3H	<10	Fail	>100
	60/40		3H	<10	Fail	>100
	70/30		3H	<30	Pass	>100
	80/20		3H	>40	Pass	>100
XP2491/G2235/M4004	40/40/20		H	<30	Pass	>100
XP2491/G3414/M4004	40/40/20		HB	>40	Pass	>100
8411/U400	50/50		3H	<20	Fail	>100
	60/40		3H	<20	Fail	>100
	70/30		2H	<40	Pass	>100
	80/20		H	>40	Pass	>100
	75/25		H	>40	Pass	>100
	73/27		2H	>40	Pass	>100
8411/U400/OL-17	65/35		2H	<20	Fail	>100

Resin	Resin Ratios	Misc.	PH	Impact	Mandrel	MEK
8411/M3130	60/40		H	<30	Pass	>100
8411/M4004	60/40		H	<30	Pass	>100
8411/U400/Nmp	60/40		3H	<20	Fail	>100
8411/U400/HDDA	73/27		H	<30	Pass	>100
8411/U400/TMPTA	73/27		2H	<30	Pass	>100
8411/U400/IBOA	73/27		H	>40	Pass	>100
8411/U400/PTTA	73/27		2H	<30	Pass	>100
8411/U400/I2100	73/27	No Cure	X	X	X	X
8411/U400/819/184	73/27		2H	>40	Pass	>100
8411/U400/819/PBZ	73/27		2H	>40	Pass	>100
XP2491/2235/BYK	50/50		F	>40	Pass	>100
XP2491/3414/BYK	50/50		B	>40	Pass	>100
8411/U400/BYK	73/27		H	>40	Pass	>100
8807/BYK			3H	>40	Pass	>100
8807/U400	50/50		3H	<10	Fail	>100
	60/40		3H	<10	Fail	>100
	70/30		3H	<30	Pass	>100
	80/20		3H	>40	Pass	>100
	90/10		2H	>40	Pass	>100
8807/U400/BYK	80/20		3H	>40	Pass	>100
8807/U400/819/184	80/20		H	>40	Pass	>100
8807/U400/819/PBZ	80/20		H	>40	Pass	>100
8807/184			F	>40	Pass	>100
8807/819/184			F	>40	Pass	>100
8807/819/PBZ			F	>40	Pass	>100
8807/U400/TMPTA/184	80/20		3H	<30	Pass	>100
8807/U400/TMPTA/BYK	80/20		4H	<30	Pass	>100
8807/TMPTA			H	>40	Pass	>100
8807/TMPTA/BYK			2H	>40	Pass	>100
8807/TMPTA	.5X PI		H	>40	Pass	>100
8807/U400/680H/TMPTA			3H	<30	Pass	>100
XP2491/U400	50/50		3H	<10	Fail	>100
	60/40		3H	<20	Fail	>100
	70/30		H	<40	Pass	>100
	80/20		F	>40	Pass	>100
	90/10		B	>40	Pass	>100
CN1963			4H	<10	Fail	>100
CN2261			4H	<10	Fail	>100
Resin	**Resin**	**Misc.**	**PH**	**Impact**	**Mandrel**	**MEK**

	Ratios					
CN962			B	>40	Pass	>100
CN996			H	>40	Pass	>100
CN9165			3H	>20	Pass	>100
CN975			3H	<10	Fail	>100
CN980		Tacky	B	>40	Pass	>100
264			3H	<30	Pass	>100
8804			2H	>40	Pass	>100
244			<B	>40	Pass	>100
270			<B	>40	Pass	>100
4833			2H	>40	Pass	>100
4883			H	>40	Pass	>100
CN9013			5H	<10	Fail	>100
8807/U400/G1121	50/50/20		H	<10	Pass	>100
M3130/HDDA	50/50		5H	<10	Fail	>100
TMPTA/HDDA	50/50		3H	<10	Fail	>100
TMPTA/IBOA	50/50		H	<30	Pass	>100
M3130/1BOA	50/50		H	<30	Pass	>100
8411/264	50/50		HB	<30	Pass	>100
8311			4H	<10	Fail	>100
	50/50		3H	<10	Fail	>100
	60/40		3H	<10	Fail	>100
	70/30		2H	<30	Fail	>100
	80/20		2H	<30	Pass	>100
996/U400	90/10		H	>40	Pass	>100
	50/50		3H	<10	Fail	>100
	60/40		3H	<10	Fail	>100
	70/30		3H	<10	Fail	>100
	80/20		3H	<30	Fail	>100
8804/U400	90/10		2H	<40	Pass	>100
	50/50		4H	<10	Fail	>100
	60/40		4H	<10	Fail	>100
	70/30		3H	<20	Fail	>100
	80/20		3H	<40	Pass	>100
4833/U400	90/10		3H	>40	Pass	>100
	50/50		3H	<10	Fail	>100
	60/40		3H	<10	Fail	>100
	70/30		2H	<30	Fail	>100
	80/20		2H	<40	Pass	>100
4883/U400	90/10		H	>40	Pass	>100

Resin	Resin Ratios	Misc.	PH	Impact	Mandrel	MEK
996/AB	10		H	>40	Pass	>100
	20		2H	<40	Pass	>100
	30		3H	<20	Pass	>100
8804/AB	10		2H	>40	Pass	>100
	20		3H	<30	Pass	>100
	30		4H	<10	Pass	>100
4833/AB	10		3H	>40	Pass	>100
	20		3H	>40	Pass	>100
	30		4H	<40	Pass	>100
8807/AB	10		2H	>40	Pass	>100
	20		2H	<30	Pass	>100
	30		3H	<10	Pass	>100
996/819/184			H	>40	Pass	>100
996/819/PBZ			H	>40	Pass	>100
4833/819/184			3H	>40	Pass	>100
4833/819/PBZ			3H	>40	Pass	>100
8804/819/184			2H	>40	Pass	>100
8804/819/PBZ			2H	>40	Pass	>100
996/BYK			H	>40	Pass	>100
4833/BYK			3H	>40	Pass	>100
8804/BYK			2H	>40	Pass	>100
8411/8311	30		3H	<40	Pass	>100
	20		2H	>40	Pass	>100
	10		HB	>40	Pass	>100
8807/8311	30		3H	<30	Pass	>100
	20		3H	<40	Pass	>100
	10		2H	>40	Pass	>100
8411/U400/LX	73/27		H	>40	Pass	>100
8411/U400/DX	73/27		H	>40	Pass	>100
8411/U400/LX/DX	73/27		2H	>40	Pass	>100

APPENDIX I - CTC/BBM UV-CURABLE JTP TESTING RESULTS

Yellow = Pass / Red = Fail

Color							
Panel ID	L	a	b	Avg. L	Avg. a	Avg. b	Delta E
Standard	49.81	-1.53	-4.26	49.72333	-1.54	-4.24333	
	49.69	-1.54	-4.24				
	49.67	-1.55	-4.23				
36173-1	49.79	-2.35	-4.18	49.71	-2.33667	-4.22	0.7903
	49.71	-2.33	-4.23				
	49.63	-2.33	-4.25				
36173-2	49.61	-2.34	-4.3	49.64	-2.32333	-4.34667	0.7904
	49.62	-2.32	-4.36				
	49.69	-2.31	-4.38				
36173-3	49.84	-2.36	-4.14	49.79333	-2.35	-4.18667	0.8152
	49.78	-2.33	-4.23				
	49.76	-2.36	-4.19				
Standard	41.06	-1.04	-4.9	40.97333	-1.04	-4.9	
	40.92	-1.04	-4.91				
	40.94	-1.04	-4.89				
36118-1	40.82	-1.45	-4.15	40.74	-1.46667	-4.13333	0.9067
	40.74	-1.47	-4.13				
	40.66	-1.48	-4.12				
36118-2	40.78	-1.47	-4.08	40.79333	-1.46333	-4.09667	0.93
	40.82	-1.47	-4.08				
	40.78	-1.45	-4.13				
36118-3	40.81	-1.46	-4.12	40.83	-1.47	-4.09667	0.942
	40.82	-1.47	-4.1				
	40.86	-1.48	-4.07				

Gloss	60 Degree Gloss				85 Degree Gloss			
Panel ID	Read 1	Read 2	Read 3	Avg.	Read 1	Read 2	Read 3	Avg.
36173-1	1.1	1	1	1.033333	1.4	1.5	1.4	1.433333
36173-2	1	1.1	1.1	1.066667	1.6	1.7	1.6	1.633333
36173-3	1	1.1	1.1	1.066667	1.4	1.5	1.6	1.5
36118-1	1.6	1.5	1.3	1.466667	3.2	2.7	2.3	2.733333
36118-2	1.6	1.5	1.5	1.533333	2.2	2.4	2.6	2.4
36118-3	1.5	1.5	1.5	1.5	3	2.9	2.7	2.866667

Wet-Tape Adhesion			
Panel	Result 1	Result 2	Avg.
36173-1	4A	4A	4A
36173-2	4A	4A	4A
36173-3	4A	4A	4A
36118-1	4A	4A	4A
36118-2	4A	4A	4A
36118-3	4A	4A	4A

GE Impact Flexibility	
Panel	Result
36173IF-1	40%
36173IF-2	40%
36173IF-3	40%
36118IF-1	40%
36118IF-2	40%
36118IF-3	40%

Low Temperature Mandrel Bend Flexibility	
Panel	Result
36173LTF-1	Pass
36173LTF-2	Pass
36173LTF-3	Fail
36118LTF-1	Pass
36118LTF-2	Pass
36118LTF-3	Pass

MEK Rubs	
Panel	Result
36173-1	>100
36173-2	>100
36173-3	>100
36118-1	>100
36118-2	>100
36118-3	>100

Final Color Readings						
Heat Resistance						
	36118 HR-1	36118HR-2	36118 HR-3	36173 HR-1	36173 HR-2	36173 HR-3
L	39.21	39.16	39.11	49.23	49.2	49.27
	39.1	39.12	39.13	49.19	49.24	49.25
	39.07	39.1	39.09	49.54	49.47	49.59
a	-1.9	-1.87	-1.87	-2.73	-2.72	-2.72
	-1.88	-1.88	-1.89	-2.73	-2.74	-2.74
	-1.85	-1.87	-1.87	-2.74	-2.72	-2.72
b	-3.72	-3.85	-3.82	-3.52	-3.6	-3.5
	-3.81	-3.8	-3.77	-3.63	-3.5	-3.61
	-3.91	-3.88	-3.89	-3.45	-3.54	-3.61
Avg. L	39.126667	39.1266667	39.11	49.32	49.303333	49.37
Avg. a	-1.8766667	-1.8733333	-1.8766667	-2.7333333	-2.7266667	-2.7266667
Avg. b	-3.8133333	-3.8433333	-3.8266667	-3.5333333	-3.5466667	-3.5733333
dE Panel	1.7135473	1.70874223	1.7008299	0.8582864	0.8370517	0.8170747

Method AHumidity Resistance				
Panel	Result		Panel	Result
UV 36173-1	4A		Control 36173-1	3A
UV 36173-2	4A		Control 36173-2	3A
UV 36173-3	4A		Control 36173-3	3A
UV 36118-1	4A		Control 36118-1	4A
UV 36118-2	4A		Control 36118-2	4A
UV 36118-3	4A		Control 36118-3	4A

Weathering Testing
500 Hours Atlas Weatherometer
Initial Color Readings

	Control 36118W-1	Control 36118W-2	UV 36118W-1	UV 36118W-2	Control 36173W-1	Control 36173W-2	UV 36173 W-1	UV 36173 W-2
L	40.16	40.15	40.83	40.64	49.8	49.66	49.9	49.83
	40.07	40.12	40.81	40.71	49.75	49.74	49.81	49.72
	40.09	40.07	40.77	40.86	49.81	49.71	49.7	49.74
a	-1.14	-1.14	-1.48	-1.5	-1.47	-1.47	-2.49	-2.45
	-1.13	-1.14	-1.49	-1.5	-1.48	-1.47	-2.42	-2.41
	-1.14	-1.14	-1.52	-1.49	-1.46	-1.46	-2.42	-2.42
b	-4.05	-4.05	-4.06	-4.1	-3.89	-3.87	-3.69	-3.85
	-4.05	-4.06	-4.07	-4.06	-3.89	-3.88	-3.8	-3.91
	-4.02	-4.05	-3.99	-4.05	-3.89	-3.89	-3.93	-3.92
Avg. L	40.10667	40.113333	40.80333	40.736667	49.786667	49.703333	49.80333	49.76333
Avg. a	-1.136667	-1.14	-1.49667	-1.496667	-1.47	-1.4666667	-2.443333	-2.42667
Avg. b	-4.04	-4.053333	-4.04	-4.07	-3.89	-3.88	-3.806667	-3.89333

Final Color Readings

	C36118W-1	C36118W-2	36118W-1	36118W-2	C36173W-1	C36173W-2	36173W-1	36173W-2
L	38.81	38.78	43.17	43.81	48.42	48.35	52.22	52.51
	38.74	38.89	43.5	44.05	48.49	48.52	52.41	51.56
	38.62	38.7	43.16	43.8	48.41	48.34	52.02	52.34
a	-1.19	-1.2	-1.79	-1.76	-1.55	-1.54	-2.49	-2.52
	-1.18	-1.19	-1.8	-1.77	-1.53	-1.54	-2.49	-2.48
	-1.27	-1.25	-1.79	-1.76	-1.56	-1.56	-2.51	-2.45
b	-4.21	-4.2	-4.32	-4.62	-4.19	-4.13	-4.65	-4.71
	-4.2	-4.19	-4.85	-4.83	-4.12	-4.12	-4.71	-4.42
	-4.17	-4.19	-4.38	-4.62	-4.16	-4.13	-4.5	-4.59
Avg. L	38.72333	38.79	43.27667	43.886667	48.44	48.403333	52.21667	52.13667
Avg. a	-1.213333	-1.213333	-1.79333	-1.763333	-1.546667	-1.5466667	-2.496667	-2.48333
Avg. b	-4.193333	-4.193333	-4.51667	-4.69	-4.156667	-4.1266667	-4.62	-4.57333
dE Panel	1.393915	1.3327374	2.536257	3.2214921	1.3749545	1.325611	2.54726	2.469478

Stencil Testing
MEK Rubs

	UV 36118	UV 36173	36118 with UV 38173	38173 with UV 36118
1	Pass	Pass	Pass	Pass
2	Pass	Pass	Pass	Pass
3	Pass	Pass	Pass	Pass
4	Pass	Pass	Pass	Pass
5	Pass	Pass	Pass	Pass
6	Pass	Pass	Pass	Pass
7	Pass	Pass	Pass	Pass
8	Pass	Pass	Pass	Pass
9	Pass	Pass	Pass	Pass

Pencil Hardness - Scratch Hardness

	UV 36118	UV 36173	36118 with UV 38173	38173 with UV 36118
1	H	F	H	F
2	F	F	F	F
3	F	F	H	F
4	H	F	F	F
5	F	F	F	F
6	H	F	F	F
7	F	F	F	F
8	F	H	F	H
9	F	F	F	F

Fluid Resistance			
		Lube Oil	
System	**Initial PH**	**Post Immersion PH**	**Pass/Fail**
36173FRL-1	F	HB	Pass
36173FRL-2	F	HB	Pass
36173FRL-3	F	HB	Pass
36118FRL-1	F	B	Pass
36118FRL-2	F	B	Pass
36118FRL-3	F	B	Pass

		Hydraulic Fluid	
System	**Initial PH**	**Post Immersion PH**	
36173FRH-1	F	HB	Pass
36173FRH-2	F	HB	Pass
36173FRH-3	F	HB	Pass
36118FRH-1	F	HB	Pass
36118FRH-2	F	HB	Pass
36118FRH-3	F	HB	Pass
		JP-8 Fuel	
System	**Initial PH**	**Post Immersion PH**	
36173FRJ-1	F	F	Pass
36173FRJ-2	F	F	Pass
36173FRJ-3	F	F	Pass
36118FRJ-1	F	HB	Pass
36118FRJ-2	F	HB	Pass
36118FRJ-3	F	HB	Pass

Cleanability				
	L Value			
Panel ID	Initial	Soil	Cleaned	Result
Control1-36173	49.75	27.02	48.84	0.949738
	49.72	26.94	48.12	
	49.63	26.5	48.69	
Control2-36173	49.64	25.51	49.77	0.9928
	49.75	26.16	49.27	
	49.58	26.47	49.42	
36173C-1	50.1	25.63	48.67	0.927876
	50.15	25.2	48.04	
	50.17	25.69	48.38	
36173C-2	50.31	26.8	48.68	0.923881
	50.14	26.94	47.81	
	50.56	26.46	49.13	
36173C-3	50.09	24.95	49.67	0.932077
	50.27	25.37	47.88	
	50.32	24.98	48.01	
Control1-36118	40.31	26.05	38.93	0.889487
	40.28	26.08	38.37	
	40.35	26.1	38.92	

Control2-36118	40.21	24.88	38.9	0.910648
	40.22	25.13	38.32	
	40.18	25.05	39.32	
36118C-1	40.96	24.48	39.72	0.867515
	40.93	23.93	37.64	
	40.77	23.98	38.64	
36118C-2	40.74	23.93	39.17	0.87786
	40.75	23.96	37.67	
	40.71	24.04	39.22	
36118C-3	40.65	24.98	39.51	0.901354
	40.74	24.11	38.4	
	40.64	24.18	39.31	

Dry Film Thickness								
	23377 Primer				UV Top Coat			
Panel	Read 1	Read 2	Read 3	Avg.	Read 1	Read 2	Read 3	Avg.
36173-1	0.9	0.9	1.1	0.966667	2.4	2.5	2.2	2.366667
36173-2	0.9	0.9	1	0.933333	2.7	2.5	1.8	2.333333
36173-3	1.1	0.9	0.9	0.966667	2.1	1.9	2.3	2.1
36118-1	0.9	0.9	0.9	0.9	2.4	2.2	2.5	2.366667
36118-2	0.9	1	1	0.966667	2	1.9	1.9	1.933333
36118-3	0.8	0.9	1.1	0.933333	2	2.2	1.7	1.966667
36173IF-1	Anodized				1.7	1.8	1.6	1.7
36173IF-2					1.8	1.8	1.4	1.666667
36173IF-3					2.1	2.5	2.5	2.366667
36118IF-1					2.1	1.9	2.1	2.033333
36118IF-2					2.4	1.9	1.6	1.966667
36118IF-3					2	1.8	1.5	1.766667
36173LTF-1					1.9	1.9	2.3	2.033333
36173LTF-2					2	1.9	2.1	2
36173LTF-3					2.1	2.4	2.1	2.2
36118LTF-1					2.1	2	1.9	2
36118LTF-2					2.2	2.1	1.9	2.066667
36118LTF-3					2	1.9	1.8	1.9
36173HR-1	1.1	1.2	1.1	1.133333	2.3	2.4	2	2.233333
36173HR-2	1	1.2	1	1.066667	2.4	2.4	2.4	2.4
36173HR-3	1	1.1	1	1.033333	2.3	2.4	2.1	2.266667
36118HR-1	0.9	0.9	1	0.933333	1.8	2.3	2.3	2.133333
36118HR-2	0.9	0.9	1	0.933333	2	2.2	2.3	2.166667
36118HR-3	0.9	1	1	0.966667	1.8	2.1	2.1	2

36173H-1	1.1	1	1	1.033333	1.8	2	1.5	1.766667
36173H-2	0.9	1.1	1	1	1.8	1.9	2	1.9
36173H-3	1	1	1.1	1.033333	1.7	2.1	1.7	1.833333
36118H-1	1	1	1	1	1.9	2	2.1	2
36118H-2	1	0.9	1	0.966667	1.4	1.3	1.3	1.333333
36118H-3	0.9	0.9	1	0.933333	1.4	1.4	1.1	1.3
36173W-1	1.1	1	1	1.033333	1.6	1.7	1.8	1.7
36173W-2	1	1.2	1	1.066667	1.7	1.8	1.9	1.8
36173W-3	1.1	0.9	1.1	1.033333	2.1	2	1.8	1.966667
36118W-1	1	1	1	1	1.8	1.8	1.8	1.8
36118W-2	1	1.1	1	1.033333	1.7	2	1.9	1.866667
36118W-3	0.9	1.1	1	1	1.8	1.4	1.4	1.533333
36173FRL-1	0.9	0.9	0.9	0.9		1.7	1.9	1.8
36173FRL-2	1	0.9	0.9	0.933333	1.6	1.7	1.7	1.666667
36173FRL-3	0.9	1.1	0.9	0.966667	1.7	1.8	1.9	1.8
36118FRL-1	0.9	1	1	0.966667	2.2	2.4	2.5	2.366667
36118FRL-2	0.9	0.9	1.1	0.966667	2.4	2.5	2.5	2.466667
36118FRL-3	1.1	0.9	1	1	2.2	2.4	2.5	2.366667
36173FRH-1	1	1	1.2	1.066667	1.8	1.8	1.8	1.8
36173FRH-2	1	0.9	1	0.966667	1.6	1.7	1.8	1.7
36173FRH-3	1	1.2	1.1	1.1	1.4	1.5	1.7	1.533333
36118FRH-1	0.9	0.9	1	0.933333	2	2.3	2.4	2.233333
36118FRH-2	0.8	1	0.9	0.9	2.1	2.3	2.3	2.233333
36118FRH-3	1	1.3	1	1.1	1.9	2	2	1.966667
36173FRJ-1	1.1	1	1	1.033333	1.8	1.8	1.7	1.766667
36173FRJ-2	1.1	1.2	1	1.1	1.8	1.9	1.9	1.866667
36173FRJ-3	1.2	1.2	1.1	1.166667	1.6	1.7	1.7	1.666667
36118FRJ-1	1.1	1	1	1.033333	2.4	2.5	2.5	2.466667
36118FRJ-2	0.9	0.9	1	0.933333	2.2	2.3	2.4	2.3
36118FRJ-3	1	0.9	0.9	0.933333	2.3	2.5	2.2	2.333333
36173S-1	1.1	1	1	1.033333	1.4	1.7	1.7	1.6
36173S-2	1	1.2	1.2	1.133333	1.5	1.7	1.8	1.666667
36118S-1	1	1	1.2	1.066667	1.5	1.6	1.5	1.533333
36118S-2	0.9	0.9	1.1	0.966667	1.6	1.6	1.7	1.633333
36173R-1	0.9	1	1	0.966667	1.4	1.6	1.7	1.566667
36173R-2	1	1.2	1.2	1.133333	1.5	1.7	1.7	1.633333
36118R-1	0.8	0.9	0.9	0.866667	1.5	1.4	1.7	1.533333
36118R-2	0.7	0.9	0.7	0.766667	1.7	1.6	1.9	1.733333